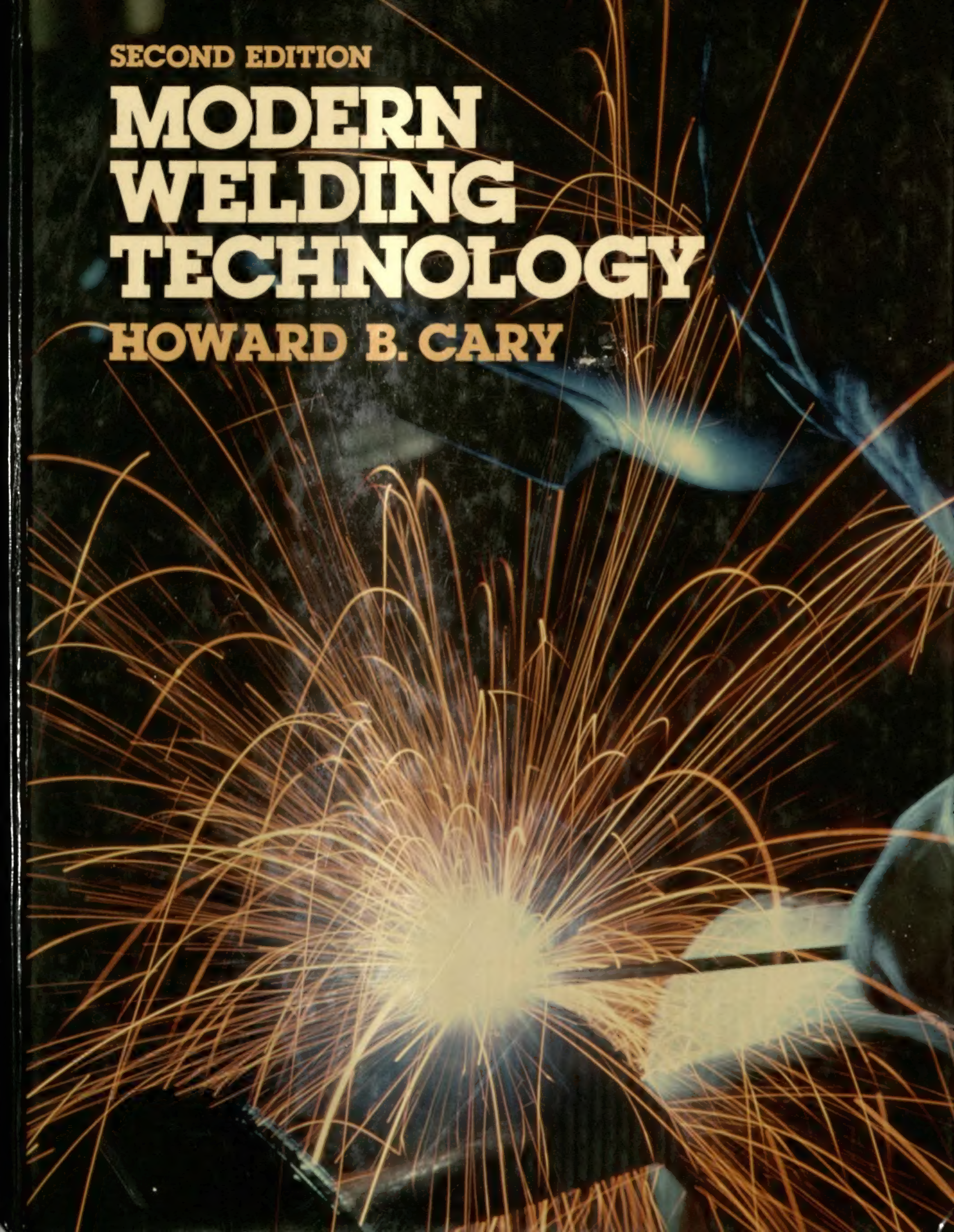
SECOND EDITION

MODERN WELDING TECHNOLOGY

HOWARD B. CARY



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MODERN WELDING TECHNOLOGY

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Contents

Preface

Many facets of welding have changed greatly in the last few years. So many changes have occurred that more than half of this book has been rewritten.

In recent years the welding industry has become more aware of the potential health hazards facing the welder. This has led to many research programs to investigate these concerns. As a result, this revision includes an entire chapter covering the safety and health of welders.

The advance in power electronic devices has permitted advances and improvements in welding machines. These changes are covered in an enlarged chapter on welding power sources. The new machines provide improved capabilities not known when this book was first published.

The introduction of computer controls for welding equipment brought about robotic welding and is starting to make truly automated welding possible and practical. Much more attention is being given to automatic, robotic, and automated arc welding.

Recent improvements in the laser, in plasma cutting, and refinements in other welding processes have received attention. Meanwhile, welding definitions have changed, specifications of welding materials have changed, new materials have become available, and welding codes have become more detailed.

This revision has given me the opportunity to rearrange and simplify some of the original material. For example, the arc welding processes have been grouped according to whether weld metal crosses the arc or not, rather than whether a constant-current or constant-voltage power source is used. The coverage of metal transfer is much more thorough. Pipe welding has been given an entire chapter. The joining of plastics and composites is now described. Coverage of other more recent techniques has been increased.

At the same time, I have stayed with the original concept. The book covers welding technology with emphasis on the arc welding process. It is a source book of welding technical information and it faithfully follows the standards, codes, and specifications published by the American Welding Society. It provides useful and necessary information for everyone involved with welding.

Howard B. Cary
Troy, Ohio

Acknowledgments

The typing of the manuscript was done by two fine efficient women who had to put up with more than they originally bargained for. Jeanne Sargent did the original and Gayle Meyers the revision. Many thanks for a job well done.

The illustrations were done by two gifted artists. Ernie Boller did the original, and I particularly enjoyed the fish in the underwater welding drawing. Russ Wogoman did the drawings in the revision. Thanks for these fine drawings, which really help tell the story.

To make this book technically accurate, the official terminology of the American Welding Society is used. The book includes information from many AWS standards and codes. The society has graciously allowed the use of this information to help us all communicate welding information more accurately. My thanks to the Society.

Hobart Brothers Company has given me permission to use their data, information, pictures, diagrams, and other material to help make this book as complete as possible. I wish specifically to thank Glenn Nally and William H. Hobart, Jr.

I want to thank the many other people who furnished information and pictures. Many thanks to each. The list is long and I hope that I have not missed anyone.

Accra-Weld Controls
Aluminum Association
American Iron & Steel Institute
American Petroleum Institute
American Society & Mechanical Engrs.
American Society for Metals
American Society of Testing & Materials
Arc Air Co.
Association of Iron & Steel Engineers

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1

Welding Background

OUTLINE

1-1 THE IMPORTANCE OF WELDING

Welding is the most efficient way to join metals. It is the only way to join two or more pieces of metal to make them act as one piece. Welding is widely used to manufacture or repair all products made of metal. Look around, almost everything made of metal is welded; the world's tallest building, moon rocket engines, nuclear reactors, home appliances, and automobiles barely start the list.

The use of welding is still increasing. If a joint is welded, it is a permanent joint. Obviously, if the joint must be disassembled occasionally, it should not be welded. Thus we should change our statement to "welding is the most economical method to permanently join metal parts." To join two members by bolting or riveting requires holes in the parts to accommodate the bolts or rivets. These holes reduce the cross-sectional area of the members to be joined by up to 10%. The joint may also require the use of one or two gusset plates, thus increasing the weight of material required and the cost. This expense can be eliminated by the use of a weld. The greatest economy of a welded design will be obtained if the cross-sectional area of the entire structural member is reduced by the amount of the bolt holes. This can be

done since the entire cross section of a member of a welded design is utilized to carry the load. The amount of material required is reduced (Figure 1-1) as well as its cost. This same design concept applies to joining plates used to build a ship or a container. In view of this material savings, ships and storage tanks are no longer riveted.

Pipes joined by welding offer similar economies. The wall thickness of a pipe should be heavy enough to carry the required load. However, if the pipe is joined by screw threads a heavier wall thickness is used to allow for cutting away a portion of the thickness for the threads (Figure 1-2). A thinner pipe wall thickness is used for the entire welded pipe system. This reduces the amount of metal required and the cost. The inside surface of the welded joint is smoother. Large-diameter pipes are no longer connected together with screw threads and pipe fittings.

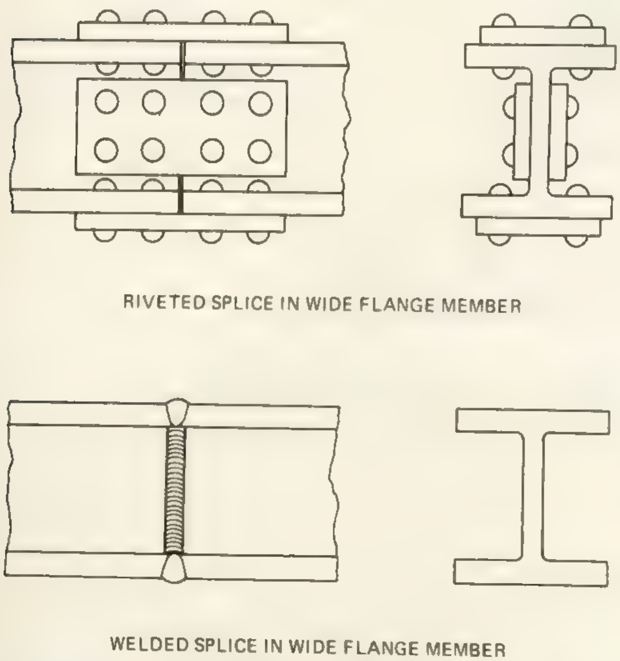
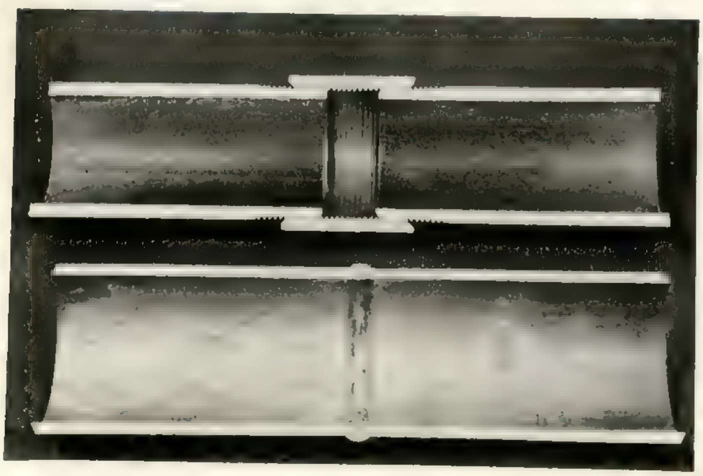


FIGURE 1-1 Comparison of welded and riveted structural joints.

FIGURE 1-2 Pipe joints welded and riveted.



Converting castings to weldments allows the designer to reduce weight by reducing metal thickness. Welding is a design concept which allows freedom and flexibility not possible with cast construction. Heavy plates can be used where strength is required and thin ones can be used where possible. The uniform thickness rule and minimum thickness required for foundry practice are not necessary for weldments. Additionally, high-strength materials can be used in specific areas, while normal strength materials are used where required.

Welding is the best way to protect and conserve materials by protecting their surface with special metal overlays. Corrosion and wear of metals account for losses running into billions of dollars annually. Together they are responsible for an untold loss of lives. Waste from both of these destructive forces can be greatly reduced by welding. Special alloys are weld-deposited on base metals to provide corrosion-resistant surfaces. Hard surfacing overlays can be made by welding to provide special alloys with wear-resistant surfaces. A typical application is the resurfacing of a cinder crusher roll with hard weld metal (Figure 1-3). Weld surfacing is used to reduce the costly abrasive and corrosive wear of machinery.

There are many ways to make a weld and there are many different kinds of welds. The welder behind the hood making sparks is using one of the more popular welding processes, known as arc welding. Some welding processes do not cause sparks; in some cases electricity is not used, and in some cases there is not even extra heat. Welding has become complex and technical. It requires considerable knowledge to select the proper welding process for critical work. Our job is to learn enough about welding so we can utilize its many advantages. Some of these advantages are:

- ☐ Welding is the lowest-cost joining method.
- ☐ It affords lighter weight through better utilization of materials.
- ☐ It joins all commercial metals.
- ☐ It can be used anywhere.
- ☐ It provides design flexibility.

It is also important to know the limitations of welding. The limitations are:

- ☐ Some welding depends on the human factor.
- ☐ It often requires internal inspection.

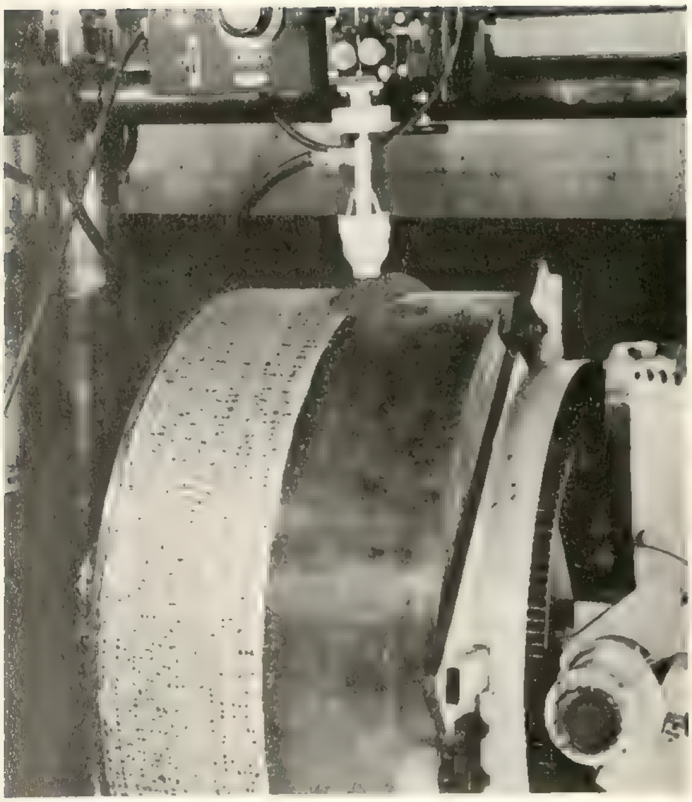


FIGURE 1-3 Overlaid part in cinder crusher roll.

Most of these limitations can be overcome by means of good controls and supervision.

Welding is also an economical manufacturing method wherever there is a need to join parts permanently. In the high-volume production industries it is common to see welding operations intermixed with bending, machining, forming, assembly, and so on. Welding is an important manufacturing process taking its place with other metalworking operations to help bring us good-quality metal products at economical prices.

1-2 WELDING JOINS ALL METALS

All metals can be joined by one welding process or another. There is a saying, "If it's metal, weld it," and it is certainly true. This should be qualified by stating that all metals commercially used for structural or strength parts are weldable. Some metals are easy to weld, and others are difficult to weld. The metals that are easily weldable can be welded in thickness from the very thinnest, about the thickness of this paper page, to the thickest or heaviest produced. The difficult-to-weld metals require special procedures and techniques that must be developed for specific applications.

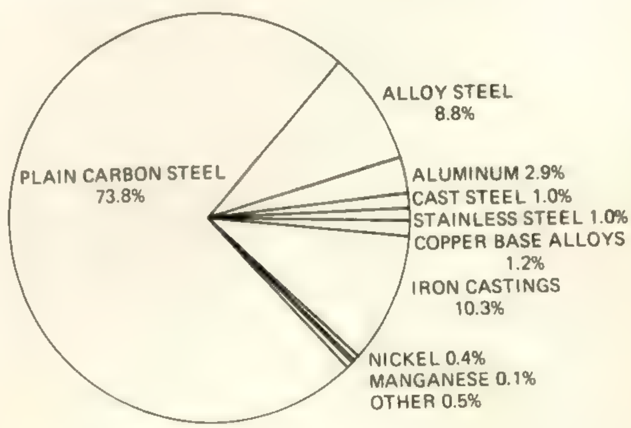
Some metals may never be welded or joined. Later chapters will provide the properties of metals such as melting temperature, density, thermal conductivity, tensile strength, ductility, and so on. These properties provide information as to whether a metal can be welded. For example, mercury is a liquid at room temperature and cannot be welded, while sodium and potassium melt just below the temperature of boiling water and are of no use as a strength member and cannot be welded. In general, metals that have a low melting temperature or low strength would not be welded. Some metals are so scarce or expensive that they would not be used where welding would be required.

The physical and mechanical properties, availability, and price all help determine if a metal will be used in applications where welding is required. The more abundant and stronger metals are those most frequently welded. Figure 1-4 shows the commercial metals according to their annual production in the United States.[1,2] This may be somewhat misleading since many metals used in the United States are imported. However, the ratio of metals is important and it is believed that these ratios represent usage and are similar in most of the industrialized countries.

Plain carbon steel is by far the most widely used metal. For this reason maximum information for welding ordinary mild steel is provided. Iron castings are shown to be the second largest type of metal produced. Most iron castings are used without welding; however, on occasion, iron castings are joined or repaired, so it is necessary to know how the various types of cast iron are welded. Alloy steels make up the next largest group of metals. This group encompasses many special types from the low-alloy high-strength steels, the heat-treated steels, the ultrahigh-strength steels, and many other classes. Each type of alloy steel involves different welding procedures which must be closely followed for successful joining.

Aluminum and aluminum alloys represent the next

FIGURE 1-4 Metal production by types in the United States. (From Refs. 1 and 2.)



largest group. Aluminum is continually finding wider application, especially when weight is a factor. The different aluminum alloys have different properties and require different procedures for welding.

Copper and copper-base alloys such as brasses and bronzes make up the next largest group. These metals are used when electrical conductivity, corrosion resistance, or heat conductivity is important. These metals are often joined and require special attention.

Stainless steel and cast steels are tied for the next position. Cast steels are normally welded like rolled steels of the same composition. There are many different types of stainless steels having specific properties. Welding procedures have been specifically developed for joining each type.

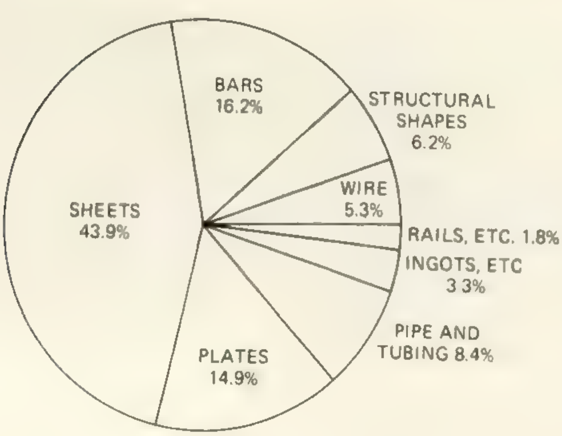
Nickel and nickel alloys represent the next largest group. This is a small percentage of the total, but it is very important since certain nickel alloys are the best metal to use for certain types of service.

The magnesium group is the smallest, though important. Magnesium is the lightest structural metal and has many applications where welding is required.

The remaining metals represent a small percentage of the total, but they are used when their particular characteristic is required and these applications often require that they be welded.

Steel is produced in many different forms. Figure 1-5 shows the production ratios of these various forms of steel.[3] Sheet steel represents the greatest volume. This is not surprising considering that most of the steel used in automobiles, trucks, buses, home appliances, office machinery, and furniture is sheet steel. It is also used for many containers, cans, and so on, and such industrial and electrical machinery. The welding of sheet metal involves many of the welding processes and is a very important segment of the welding industry.

FIGURE 1-5 Steel production by types in the United States. (From Ref. 3.)



Steel bars represent the second largest product form. Many bars are machined or cut and used, but a sizable portion of bars go with structural shapes, the fourth largest group, and are used in the construction industry for building bridges, and buildings.

Steel plates represent the third largest group and are used to make tanks, boilers, machinery, ships, and other weldments.

Pipe and tubular products represent the fifth largest group. All large-diameter pipe and much of the smaller pipe is joined by welding. The welding of pipe requires special techniques and procedures.

The remaining groups—wires, rails, and ingots—may not involve much welding. However, rails are now being welded for the railroads. Ingots may be rolled into other forms, and wire and rods are usually drawn to small diameter for their end use.

Thus we can see the broad use of metal, especially the steels, and how welding relates to them. It is important that we know how to weld each metal in any form.

Information about each metal is provided by specifications. Most specifications are originated by engineering societies, technical groups, and trade associations, which group the metals according to composition, strength, or some other characteristics. Later chapters are devoted to metal groupings, steels, nonferrous metals, and so on, and the specifications are explained.

A summary of metals according to composition groupings is given in Figure 1-6. They are related to the more common welding processes, and a rating system is given which indicates how they can be welded.

All metals *can* be welded, but some are easier to weld than others. In other words, they possess **weldability.** Weldability is defined as "the capacity of materials to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service." All metals cannot be joined by each welding process. Actually, some of the newer welding processes were developed to join specific metals. Certain metals are known as "difficult to weld," which means that specific precautions and procedures are required to produce efficient joints. Other factors complicate the making of successful welds. The thickness of the metal section involved is a factor that must be considered.

A major accomplishment of the welding industry has been to develop materials to join these different metals and alloys. These materials, or **filler metals** as they are commonly called, fill the weld joint and provide joints as strong as the metals being joined.

The term "filler metals" means "the metal to be added in making a welded, brazed, or soldered joint" and includes electrodes and welding rods. The term can be broadly interpreted to cover shielding methods, including

	Welding Processes[a]								
Base Metals Welded	Shielded Metal Arc	Gas Tungsten Arc	Plasma Arc	Submerged Arc	Gas Metal Arc	Flux Cored Arc	Electroslag	Braze	Gas
Aluminums	C	A	A	No	A	No	Exp	B	B
Copper-base alloys									
Brasses	No	C	C	No	C	No	No	A	A
Bronzes	A	A	B	No	A	No	No	A	B
Copper	C	A	A	No	A	No	No	A	A
Copper nickel	B	A	A	No	A	No	No	A	A
Irons									
Cast, malleable, nodular iron	A	B	B	No	B	B	No	A	A
Wrought iron	A	B	B	A	A	A	No	A	A
Lead	No	B	B	No	No	No	No	No	A
Magnesium	No	A	B	No	A	No	No	No	No
Nickel-base alloys									
Inconel	A	A	A	No	A	No	No	A	B
Nickel	A	A	A	C	A	No	No	A	A
Nickel silver	No	C	C	No	C	No	No	A	B
Monel	A	A	A	C	A	No	No	A	A
Precious metals	No	A	A	No	Exp	No	No	A	B
Steels									
Low-carbon steel	A	A	A	A	A	A	A	A	A
Low-alloy steel	A	A	A	A	A	A	A	A	A
High- and medium-carbon steel	A	A	A	B	A	A	A	A	A
Alloy steel	A	A	A	B	A	A	A	A	A
Stainless steel	A	A	A	A	A	B	A	A	A
Tool steel	A	A	A	No	C	No	No	A	A
Titanium	No	A	A	Exp	A	No	No	No	No
Tungsten	No	B	A	No	No	No	No	No	No
Zinc	No	C	C	No	No	No	No	No	C

[a]Metal or process rating: A, recommended or easily weldable; B, acceptable but not best selection or weldable with precautions; C, possibly usable but not popular or restricted use or difficult to weld; no, not recommended or not weldable.

FIGURE 1-6 Summary of metals welded by various processes.

fluxes and gases. The filler metals and materials for welding are explained in Chapter 13.

1-3 HISTORICAL DEVELOPMENT OF WELDING

Welding, which is one of the newer metalworking trades, can trace its historic development back to ancient times. The earliest example comes from the Bronze Age. Small gold circular boxes were made apparently by pressure welding lap joints together. It is estimated that these boxes were made more than 2000 years ago and are presently on exhibit at the National Museum in Dublin, Ireland. During the Iron Age the Egyptians and other people in the eastern Mediterranean area learned to weld pieces of iron together. Many tools and weapons have been found which were made approximately 1000 B.C. Items of this type are on exhibit in the British Museum in London. Other examples of early welded art are displayed in the museums of Philadelphia and Toronto. Items of iron and bronze that exhibit intricate forging and forge welding operations have been found in the pyramids of Egypt.

During the Middle Ages the art of blacksmithing was developed to a high degree and many items of iron were produced which were welded by hammering. One of the largest welds from this period was the Iron Pillar of Delhi in India, which was erected about the year A.D. 310. It was made from iron billets welded together. It is approximately 25 ft (7.6 m) tall with a diameter of 12 in. (300 mm) at the top and 16 in. (400 mm) at the bottom.

Its total weight is 12,000 lb (5.4 metric tons). Other pillars were erected in India at about this same time and a few other large weldments made by the Romans have been discovered in Europe and in England. Other examples of welded work have been found in Scandinavia and in Germany. However, it was not until the nineteenth century that welding as we know it today was discovered.

Sir Humphry Davy of England is credited with providing a foundation for modern welding with two discoveries. One was the discovery of acetylene and the second was the production of an arc between two carbon electrodes using a battery. In the mid-nineteenth century, the electric generator was invented and arc lighting became popular. The period 1877–1903 provided a great number of discoveries and inventions pertaining to welding. During this period gas welding and cutting were developed. Arc welding with the carbon arc and metal arc was developed and resistance welding, much as it is known today, became a practical joining process. Auguste De Meritens, working in the Cabot Laboratory in France, used the heat of an arc for joining lead plates for storage batteries in the year 1881. It was his pupil, however, the Russian, Nikolai N. Benardos, working in the French laboratory, who was granted a patent for welding. He, with a fellow Russian, Stanislaus Olszewaski, secured a British patent in 1885 and an American patent in 1887.[4] The patents show the forerunner of today's electrode holder (Figure 1-7). This work was the actual beginning of arc welding or at least carbon arc welding. Benardos's efforts were apparently all restricted to carbon arc welding, although he was able to weld iron as well as lead. Carbon arc welding became increasingly popular during the late 1890s and early 1900s.

Apparently, Benardos was not successful with a metallic electrode, and in 1890, C. L. Coffin of Detroit was awarded the first U.S. patent for an arc welding process using a metal electrode.[5] This was the first record of the metal melted from the electrode actually carried across the arc to deposit filler metal in the joint to make a weld. At about the same time, N. G. Slavianoff, a Russian, presented the same idea of transferring metal across an arc, but to cast metal in a mold.[6]

In about 1900, Strohmenger introduced a coated metal electrode in Great Britain.[7] There was a thin wash coating of clay or lime, but it did provide a more stable arc. Oscar Kjellberg of Sweden invented the covered or coated electrode during the period 1907 to 1914. Figure 1-8 shows his concept of welding with coated stick electrodes.[8] They were produced by dipping short lengths of bare iron wire in thick mixtures of carbonates, silicates, and so on, and allowing the coating to dry. Wash-coated electrodes and the dipped-type covered electrode are still manufactured in some countries.

Meanwhile, the resistance welding processes were

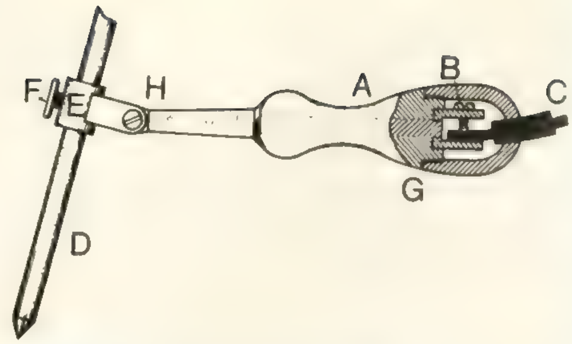
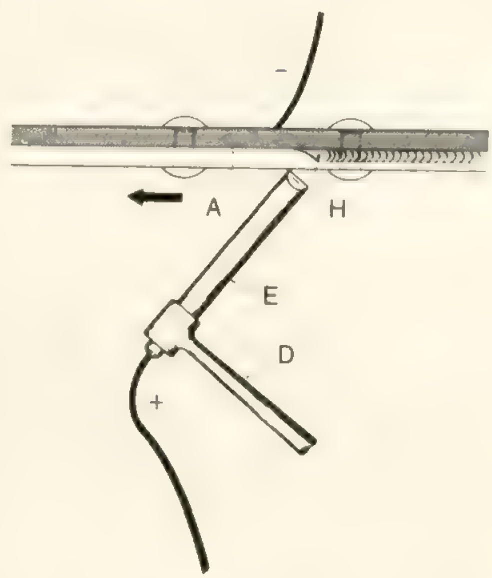


FIGURE 1-7 First electrode holder.

FIGURE 1-8 Kjellberg covered electrode.



developed, including spot welding, seam welding, projection welding, and flash butt welding. Elihu Thompson is given credit for originating resistance welding. His series of patents began in 1885. He originated a company which later bore his name, the Thompson Electric Welding Company and developed the different resistance welding processes between that time and 1900.

Thermit welding was invented by a German named Goldschmidt in 1903 and was used to weld railroad rail.[9]

Gas welding and cutting were also perfected in this period. The production of oxygen, and later the liquefying of air, along with the introduction in 1887 of a blow pipe or torch, helped the development of both welding and cutting. Before 1900 hydrogen and coal gas were used with oxygen. However, in about 1900 a torch suitable for use with low-pressure acetylene was developed and the oxyacetylene gas welding and cutting processes were launched.

World War I brought a tremendous demand for

metal material production, and welding was pressed into service. Many companies sprang up in America and in Europe to manufacture various types of welding machines and electrodes to meet this requirement. Many innovations were tried and most were successful. The British built the first all-welded ship, H.M.S. *Fulagar,* and the Dutch started to weld fuselages of fighter planes. Perhaps the most famous incident was the repair work on German ships interned in New York harbor that were sabotaged by their crews. By means of arc welding these ships were quickly repaired and put back into service to deliver material from the United States to Europe.

Immediately after the war, in 1919, twenty members of the Wartime Welding Committee of the Emergency Fleet Corporation, under the leadership of Comfort Avery Adams, founded the American Welding Society. It was founded as a nonprofit organization dedicated to the advancement of welding and allied processes.

Alternating-current welding was invented in 1919 by C. J. Holslag,[10] however, it did not become popular until the 1930s, when the heavy-coated electrode found widespread use.

In 1920, automatic welding was introduced. It utilized bare electrode wire operated on direct current and utilized arc voltage as the basis of regulating the feed rate of the electrode wire. Automatic welding was invented by P. O. Nobel of the General Electric Company.[11] It was used to build up worn motor shafts and worn crane wheels. It was also used by the automobile industry to produce rear axle housings.

During the 1920s various different grades and types of welding electrodes were developed and made available. Mild steel with a carbon of 0.20% or less was used for welding practically all grades of rolled steel. Higher-carbon electrodes and alloy steel electrodes were also developed. Copper alloy rods were developed for carbon arc welding and brazing.

There was considerable controversy during the 1920s about the advantage of the heavy-coated rods versus light- or wash-coated rods. Heavy-coated rods made by dipping were more expensive. Coating applied by extrusion on the rod was less expensive. The heavy-coated electrodes, which were made by extruding the coating on the bare rod, were developed by Langstroth and Wunder of A. O. Smith Company[12] and were used by the company in 1927. In 1929, Lincoln Electric Company produced extruded electrode rods and these were sold to the public. By 1930, covered electrodes had come into their own and specifications were being written for them. At the same time welding codes appeared which required higher-quality weld metal, and this in turn increased the use of covered electrodes.

During the 1920s there was considerable interest in shielding the arc and weld area by externally applied gases. It was realized that the atmosphere of oxygen and nitrogen in contact with the molten weld metal caused brittle and sometimes porous welds. In view of this, research work was done to utilize gas-shielding techniques. Alexandre and Langmuir did considerable work in chambers using hydrogen as a welding atmosphere. They utilized two electrodes starting with carbon electrodes but later changing to tungsten electrodes. The hydrogen was changed to atomic hydrogen in the arc. It was then blown out of the arc forming an intensely hot flame of atomic hydrogen burning to the molecular form and liberating heat. This arc produced half again as much heat as an oxyacetylene flame. This was named the atomic hydrogen welding process. Atomic hydrogen never became extremely popular but was used during the 1930s and 1940s for special applications of welding and later on for welding of tool steels.

During this period H. M. Hobart and P. K. Devers were doing similar work but using atmospheres of argon and helium. In their patents applied for in 1926, arc welding utilizing gas independently supplied around the arc was a forerunner of the gas tungsten arc welding process.[13,14] They also showed welding with a concentric nozzle and with the electrode being fed as a wire through the nozzle. This was the forerunner of the gas metal arc welding process. Neither of these processes was developed until later.

The covered electrode became the mainstay of the welding industry, even though it was applied manually. At the same time many efforts were made to improve automatic welding utilizing bare wire. Such efforts included the use of a covering on electrodes which were then coiled and at the welding point the coating was milled away to introduce welding current to the core wire. Another method, the Una-method, utilized a woven screen of fine wire saturated with coating material, which was then wrapped around the electrode wire as it was fed into the arc below the current contact point. This process had some commercial utilization, but never became too popular. The Fusarc process developed in England was another variation, and here small wires were wrapped around the main large electrode wire and the areas between were filled with coating material. This process became popular in Europe and is still used in Great Britain.

One of the more specialized welding processes was developed in 1930 at the New York Navy Yard. This process, known as stud welding, was developed specifically for attaching wood decking over a metal surface.[15] The process welded studs, screws, and so on, to the base metal by means of a special gun, which automatically controlled the arc. Fluxing elements on the end of the stud improved the properties of the weld. Stud welding became popular in the shipbuilding and construction industries and in manufacturing.

FIGURE 1-9 Meredith Heliarc torches.

The automatic process that became extremely popular was the submerged arc welding process. This "under powder" or smothered arc welding process was developed by the National Tube Company for a new pipe mill at McKeesport, Pennsylvania. It was designed to make the longitudinal seams in the pipe. This process was patented by Robinoff in 1930[16] and it was later sold to Linde Air Products Company, where it was renamed Unionmelt[17] welding. Submerged arc welding was used during the defense buildup in the late 1930s and early 1940s in both the shipyards and in ordnance factories. It is one of the most productive welding processes and remains popular today.

Gas tungsten arc welding had its beginnings from an idea by C. L. Coffin to weld in a nonoxidizing gas atmosphere, which he patented in 1890.[5] The concept was further refined in the late 1920s by Hobart, when he used helium for shielding, and Devers, who used argon. The threat of World War II indicated the need to weld magnesium to build fighter planes. Engineers of the Northrup Aircraft Company, in conjunction with Dow Chemical Company, began a program to develop a welding process for joining magnesium. The inert gas-shielded process developed by Hobart and Devers was ideal for welding magnesium and also for welding stainless and aluminum. It was perfected in 1941, patented by Meredith, and named Heliarc welding, since helium was initially used for shielding.[18] Figure 1-9 shows early torches developed by Meredith. It was later licensed to Linde Air Products, where the water-cooled torch was developed. The gas tungsten arc welding process has become one of the most important arc welding processes.

The other concept invented by Hobart and Devers was the gas-shielded metal arc welding process successfully developed at Battelle Memorial Institute in 1948 under the sponsorship of the Air Reduction Company. This development utilized the gas-shielded arc similar to the gas tungsten arc, but replaced the tungsten electrode with a continuously fed electrode wire.[19] Figure 1-10 shows the first practical gas metal arc welding gun designed by the author. One of the basic changes that made the process more acceptable was the use of small-diameter electrode wires and the constant-voltage principle of control and power source. This principle had been patented earlier by H. E. Kennedy.[20] The initial introduction of GMAW was for welding nonferrous metals, particularly heavy aluminum plate. The high deposition rate led users to try the process on steel. The cost of inert gas was relatively high and the cost savings were not immediately available.

FIGURE 1-10 First gas metal arc semiautomatic gun

In 1953, Lyubavskii and Novoshilov announced the use of welding with consumable electrodes in an atmosphere of CO_2 gas.[21] The CO_2 welding process immediately gained favor since it utilized equipment developed for inert gas metal arc welding but could now be used for economically welding steels. The CO_2 arc is a hot arc and the larger electrode wires required fairly high currents. Efforts were made to make the process

more acceptable for the welder and this in turn led to smaller-diameter electrode wires and refined power supplies. The outcome of this development was the short-circuit arc variation which was known as Micro-wire, short arc, and dip transfer welding, all of which appeared late in 1958 and early in 1959. This variation of the process allowed all-position welding on thin materials. It soon became the most popular of the gas metal arc welding process variations.[22]

Another variation was the use of inert gas with small amounts of oxygen which provided the spray-type arc transfer. This variation became popular in the early 1960s for welding agricultural equipment. The latest variation of gas metal arc welding is the use of pulsed current. In this variation the current is switched from a high value to a low value at a rate of once or twice the line frequency. Now variable frequency is used.

Soon after the introduction of the CO_2 welding process a variation utilizing a special electrode wire was developed. This wire, described as an inside–outside electrode, was tubular in cross section with the fluxing agents on the inside. These wires could be used in the same equipment as the gas metal arc welding process. The process was called Dualshield, which indicates that external shielding gas was utilized, as well as the gas produced by the flux in the core of the wire, for arc shielding. This process, invented by Bernard, was announced in 1954 but was patented in 1957, at which time it was reintroduced by the National Cylinder Gas Company.[23]

Soon afterward, in 1959, an inside–outside electrode was produced which did not require external gas shielding. Initially, the weld deposits were of lower quality. The absence of shielding gas gave the process popularity for noncritical work. This process was the self-shielding process later called Innershield by Lincoln Electric Company. Both the gas-shielded and self-shielding systems are widely used today and are growing in popularity.[24]

The electroslag welding process was announced to the Western world by the Soviets at the Brussels World's Fair in Belgium in 1958. It had been used in the Soviet Union since 1951 but was based on work done in the United States by R. K. Hopkins, who was granted patents in 1940.[25] The Hopkins process, as it was then called, was never used to a very great degree for joining. Figure 1-11 shows the Hopkins process for joining steel pieces. In the Soviet Union there was a large demand for heavy weldments in order to build large machines and tools. The process was perfected and equipment was developed at the Paton Institute Laboratory in Kiev, Ukraine, USSR, and also at the Welding Research Laboratory in Bratislava, Czechoslovakia. The first production use in the United States was at the Electromotive Division of General Motors Corporation in Chicago, where it was called the Electro-molding process. It was announced in December 1959 for the fabrication of welded diesel engine blocks.[26] The process and its variation, using a con-

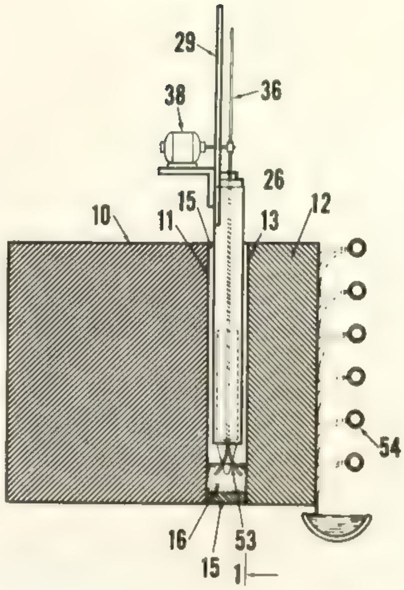


FIGURE 1-11 Hopkins electroslag welding.

sumable guide tube, have become popular and are widely used for welding thicker materials.

Another vertical welding method, called Electrogas, was introduced in 1961 by the Arcos Corporation.[27] It utilized equipment developed for electroslag welding but employed a flux-cored electrode wire and an externally supplied gas shield. It is an open arc process since a slag bath is not involved. It is a variation of flux-cored arc welding. A newer development uses self-shielding electrode wires and a variation uses solid wire but with gas shielding. These methods allow the welding of thinner materials than can be welded with the electroslag process.

The plasma arc welding process, which is very similar to gas tungsten arc welding, was invented by Gage in 1957.[28] Plasma arc welding uses a constricted arc or an arc through an orifice, which creates an arc plasma that has a higher temperature than the tungsten arc. It is also used for metal spraying and for cutting. As a cutting process it became popular for nonferrous metals. It is used for spraying both wires and powders. Plasma arc welding is popular for low-current welding and is becoming increasingly popular in higher-current applications.

The electron beam welding process, which uses a focused beam of electrons as a heat source in a vacuum chamber, was developed in France in the mid-1950s. J. A. Stohr of the French Atomic Energy Commission made the first public disclosure of this welding process at a symposium on fuel elements held in Paris on November 23, 1957.[29]

Electron beam (EB) welding has gained widespread acceptance for welding. Its popularity is increasing due to recent developments in Japan for welding heavy-wall pressure vessels. In the United States the automotive and

aircraft engine industries are major users of EB welding. More and more applications are being found for this process, which should grow in popularity in the future.

Friction welding, which uses high rotational speeds and upset pressure to provide friction heat, was developed in the Soviet Union, but additional work was done in Great Britain and the United States. It is a specialized process and has applications only where a sufficient volume of similar parts are to be welded because of the initial expense of equipment and tooling. This process, also called inertia welding, will find more uses and will become more popular.

The newest of the welding processes is laser welding. The laser originally developed at the Bell Telephone Laboratories was used as a communications device. Because of the tremendous concentration of energy in a small space it proved to be a powerful heat source. It has been used for cutting metals and other materials. The early problems involved short pulses of energy; however, today continuous-pulse equipment is available. The equipment is still extremely expensive and bulky, but in time it should be reduced in cost and size. The laser is now finding welding applications in routine metalworking operations.

There are many other variations of these processes, which are not specifically processes themselves. These will be discussed along with the basic process. Undoubtedly, additional welding processes and methods will be developed and as the need arises they will be adapted to metalworking requirements.

1-4 THE WELDING INDUSTRY AND ITS FUTURE

Welding is now the universally accepted method of permanently joining metals. It is considered a mature industry but it is still a growing industry on a world wide basis. The true impact of welding on the metalworking industry should be measured in the value of the parts produced by welding, the amount of money saved by the use of welding over other metal fabrication processes, and in the value of products made possible by welding. However, this information is impossible to determine.

Historical data are available that record the growth of the welding equipment and materials industry. A record of the industry since 1970 (Figure 1-12) shows growth greater than the gross national product for the country. Conventional electric arc welding equipment and filler metals represent over two-thirds of this total. Each segment of the industry and each welding process has its own growth patterns.

In order to make a projection we must determine the past historic growth patterns, determine the present position, and consider those factors that will have an impact on the growth in the future. Future growth of the arc welding processes depends on factors that may have an impact on the industries served by welding. The welding industry relates to the steel and other metals industries. As more metals are used, more welding equipment and filler metals will be required. A convenient starting point for such an analysis is to consider Figure 4-4, which shows industries that use welding to the greatest degree. The future of these industries will largely determine the future of welding. Another clue is provided by the data shown in Figure 1-4, which shows the amount and type of metal produced in the country. These data relate to processes and welding methods. Another indicator is Figure 1-5, which shows the types of steel most widely used throughout the country.

It is possible to estimate the amount of each type of arc welding that is being done in the United States and how it is being applied. The most suitable data for a starting point are shown in Figure 1-13. This shows the amount and percentage of filler metals sold based in the following categories:

1. Covered electrodes (stick electrodes) all types
2. Submerged arc welding electrode wire [solid steel larger than 1/16 in. (1.6 mm) in diameter]
3. Gas metal arc welding electrode wire [solid steel wire 1/16 in. (1.6 mm) and smaller]
4. Flux-cored arc welding electrode wire

At this point we can project into the future. This is done by charting the bar graph information into line charts and extending these lines for five years (Figure 1-14). This shows that based on the percentage of the total:

- ☐ Covered electrodes have been decreasing steadily for the last 14 years dropping from 72% to 49% and projected to 40%.
- ☐ Submerged arc welding has remained constant at about 5 to 7%.
- ☐ Gas metal arc welding has almost doubled, rising from 10% to 20%, and is projected to almost double again.
- ☐ Flux-cored welding is increasing, but at a slower rate.

This information shows that semiautomatic welding will greatly increase, machine and automatic welding will increase modestly, but manual welding is decreasing at least as a percentage of the total.

After analyzing recent trends in welding and manufacturing it becomes evident that the following must be considered with regard to the future of welding:

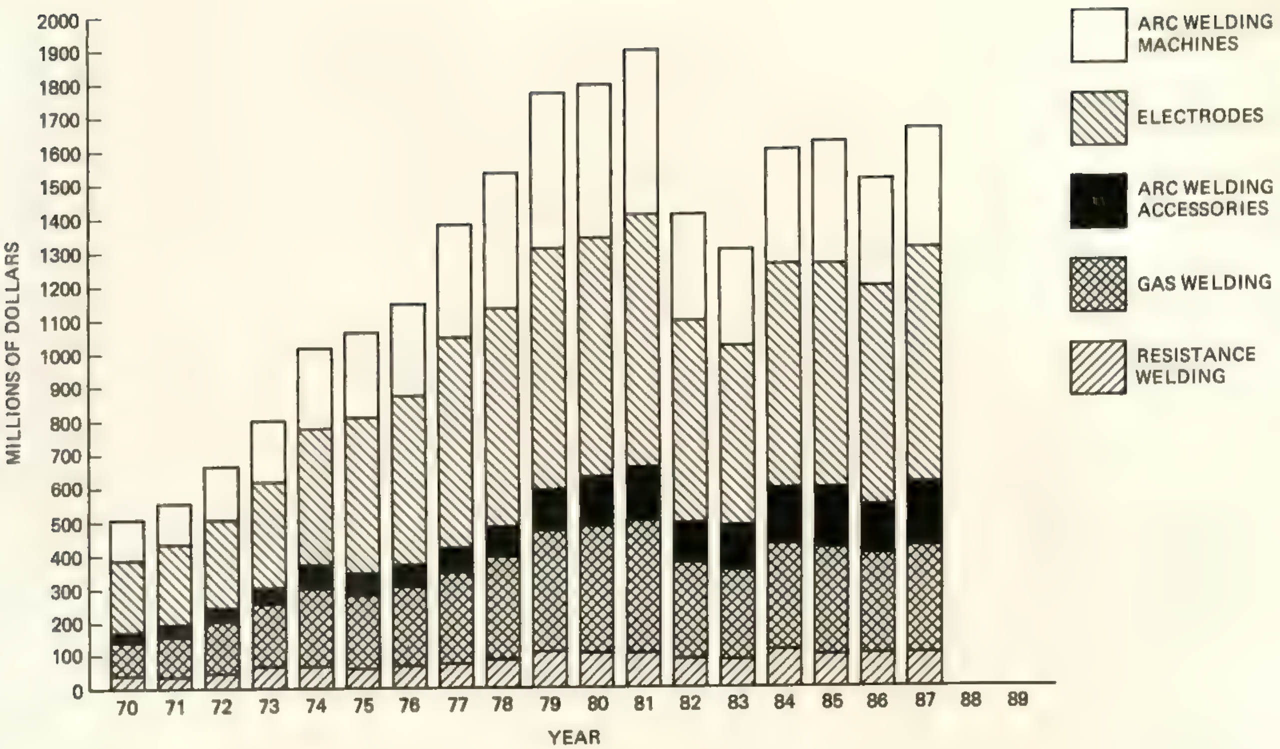


FIGURE 1-12 Welding industry sales in the United States. (From Ref. 30.)

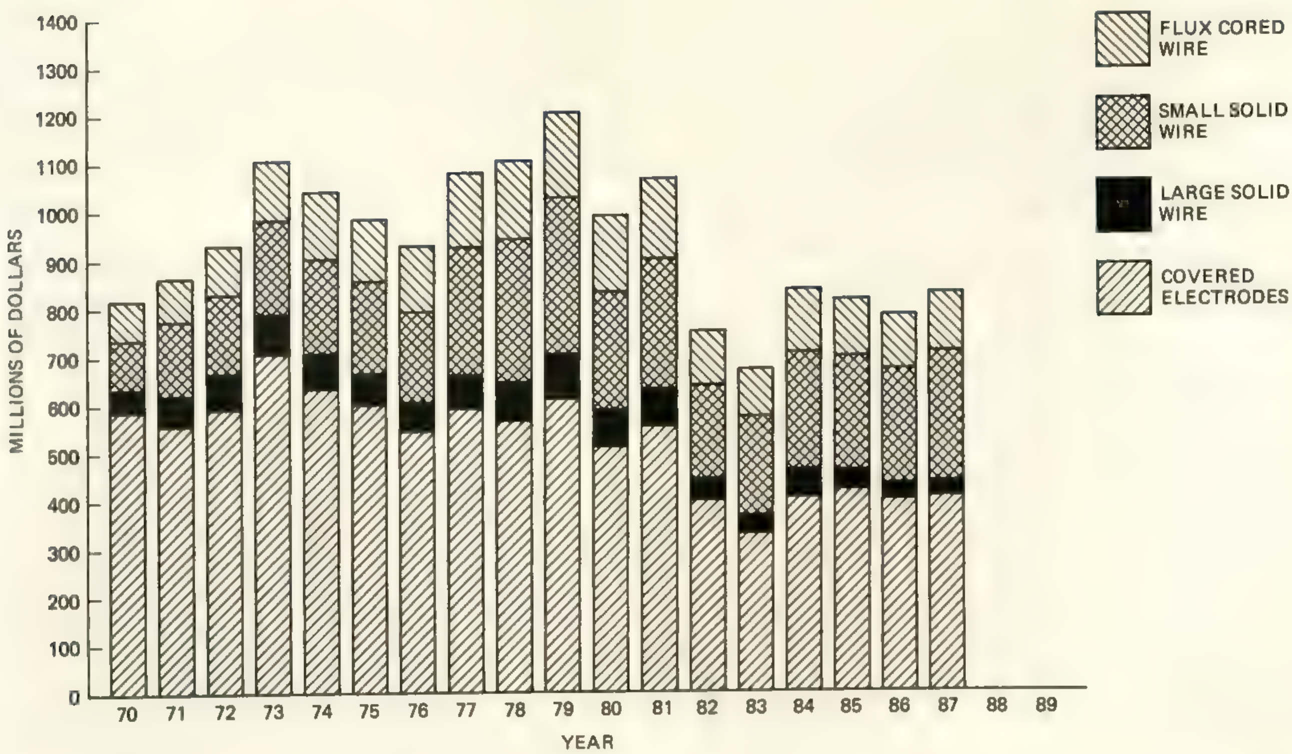


FIGURE 1-13 Welding filler metal sales in the United States. (From Ref. 30.)

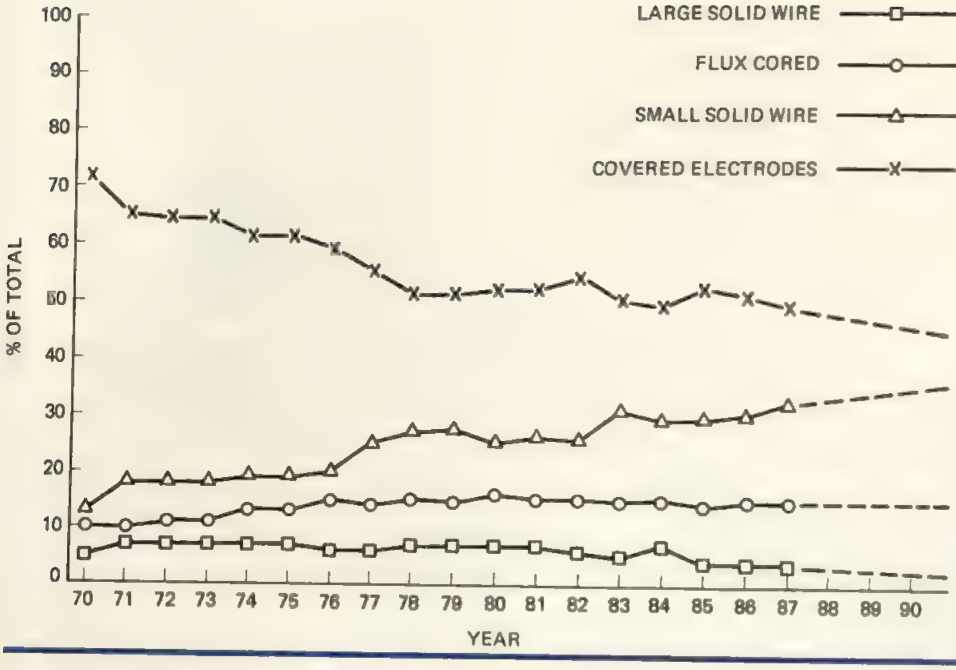


FIGURE 1-14 Filler metal sales and projections for the United States based on percentage of types.

1. There will be continuing need to reduce manufacturing costs and to improve productivity, since:
   (a) Wage rates for the people in manufacturing industries will continue to increase.
   (b) The cost of metals for producing weldments and filler metals will continue to be more expensive.
   (c) Energy and fuel costs will increase and shortages may occur.
2. There will be a continuing trend toward the use of higher-strength materials, particularly in the steels and lighter-weight materials.
3. There will be more use of welding by manufacturing industries, probably decreasing the use of castings.
4. There will be a trend toward higher levels of reliability and higher-quality requirements.
5. The trend toward automatic welding and automation in welding will accelerate.

Productivity is the amount of welding that can be done by a welder in a day. This is determined by several factors, the most important is the operator factor or duty cycle. Operator factor for a welder is the number of minutes per eight-hour period that is spent actually welding. The different methods of welding have different average duty cycles. Manual welding has the lowest operator factor with semiautomatic welding approximately double and machine welding the next highest, with automatic welding approaching 100%. Efforts will be made to utilize those processes that have the highest-duty cycles. The expected trend will be away from manual welding toward semiautomatic welding and to machine or automatic welding when possible.

Another factor affecting productivity relates to the deposition rate of the welding process. The higher current processes have the highest deposition rates, thus submerged arc welding and electroslag welding will remain important as costs must be reduced.

The next factor deals with increasing material costs. It is imperative to obtain the maximum utilization of filler metals. The cold-wire-type processes, gas tungsten arc and plasma arc, can deposit 100% of the filler metal purchased. Submerged arc welding, when the electrode only is considered, approaches 100% as does electroslag welding. Gas metal arc welding will give about 95% utilization. Flux-cored welding is the lowest of the continuous wire processes, normally in the 80+% range. Covered electrodes have the lowest utilization because of the stub end and coating loss that results in approximately 65% of the weight of the filler metals purchased actually being deposited in the weld joint.

Another factor closely related to filler metal efficiency and operator factor is the total deposit of weld metal to produce a given weldment. If the amount of weld metal can be reduced to make a weld it is an economic savings, thus there is an advantage to methods such as narrow gap welding. The higher penetration characteristics of CO_2 welding gives it an advantage over shielded metal arc welding because fillet weld sizes can be reduced and the same weld strength retained.

In forecasting the arc welding field, we will consider each process separately since each has its own historical development and utilization and will have a different future. However, the arc welding processes will continue to dominate the welding industry.

The shielded metal arc welding process is the oldest of the current arc welding processes but is losing ground in the total arc welding market. This trend will continue and manual electrode welding will represent only 40% in a few years.

The percentage of filler metal used by submerged arc welding has remained almost constant through the years. It is impossible to differentiate between filler metal used for electroslag welding and submerged arc welding; however, both processes will hold steady.

Gas metal arc welding will continue to accelerate since it is being substituted for shielded metal arc, gas welding, brazing, and resistance welding. This process, since it is a continuous wire process with high filler metal utilization, will continue to rise at the highest rate.

The flux-cored arc welding process started from a lower base and has been gaining modestly. This trend will continue; however, lower filler metal utilization and higher filler metal cost will keep it from growing as fast as gas metal arc welding.

Gas tungsten arc welding will grow as fast or faster than the total welding market. There are three reasons: (1) it will weld all metals, (2) it is being used on high-quality work, and (3) it can be used for welding newer, thin, specialty metals.

Plasma arc welding will grow faster than gas tungsten arc as soon as its capabilities are better known.

Robotic arc welding will become increasingly important. Specialized automatic welding machines will soon be specified by the type of work and the size of work they are expected to perform. Numerically controlled machines, and computer-controlled machines will become more commonplace in the years ahead. Every effort will be made to reduce the amount of manual labor involved in making welds.

Some of the newer processes and some which are of a more specialized nature will grow quite rapidly; however, they will never become large segments of the total welding industry. These include electron beam welding, laser beam welding, friction welding, ultrasonic welding, diffusion welding, and cold welding.

With increased emphasis on welding as a basic manufacturing technology the growth rate in the future will approximate 8% per year and welding equipment shipments are expected to more than double. Growth rate is expected to be shared by all of the different welding processes. However, the more conventional arc welding processes will not grow as fast as the more exotic processes because of a larger base.

QUESTIONS

1-1. Why is welding the most economical way to join metals permanently?

1-2. Why can thinner-wall pipe be used with welded joints?

1-3. Why do bolt holes reduce the strength of a bolted butt splice joint?

1-4. What are five advantages of welded construction?

1-5. What metal is not welded?

1-6. What metal is most often welded?

1-7. Are all other metals welded with equal ease?

1-8. Steel is produced in many forms. What type is most popular?

1-9. What is weldability?

1-10. What is a welding filler metal?

1-11. What ancient people used welding 2000 years ago?

1-12. What two important welding discoveries were made by Sir Humphry Davy of England?

1-13. When was arc welding, as we know it today, invented?

1-14. Who invented metal arc welding?

1-15. Who invented the heavy-covered electrode?

1-16. When was automatic welding first used?

1-17. What is the electrode utilization factor for a covered electrode?

1-18. Why is this utilization factor so low?

1-19. Who is considered the inventor of GTAW? When was it put into practical use?

1-20. What arc welding process seems to be growing fastest?

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2

Fundamentals of Welding

OUTLINE

2-1 BASIC DEFINITIONS

To understand welding it is necessary to be familiar with some of the basic terms used by the industry. The American Welding Society (AWS) provides the majority of definitions,[1] and many of these are given in this chapter and throughout the book. The official AWS definitions will be used. There are, however, some slightly obscure definitions and slang terms. These and the AWS terms will be presented in Section A-1 of the Appendix.

Welding is a materials-joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal. It is used to make welds. A **weld** is "a localized coalescence of metals or nonmetals produced either by heating materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler metal." **Coalescence** means the growing together or growth into one body of the materials being welded. The word "coalescence" is no longer used in all the welding process definitions since these definitions use the word "weld," defined above.

A **weldment** is an assembly whose component parts are joined by welding. A weldment can be made of many

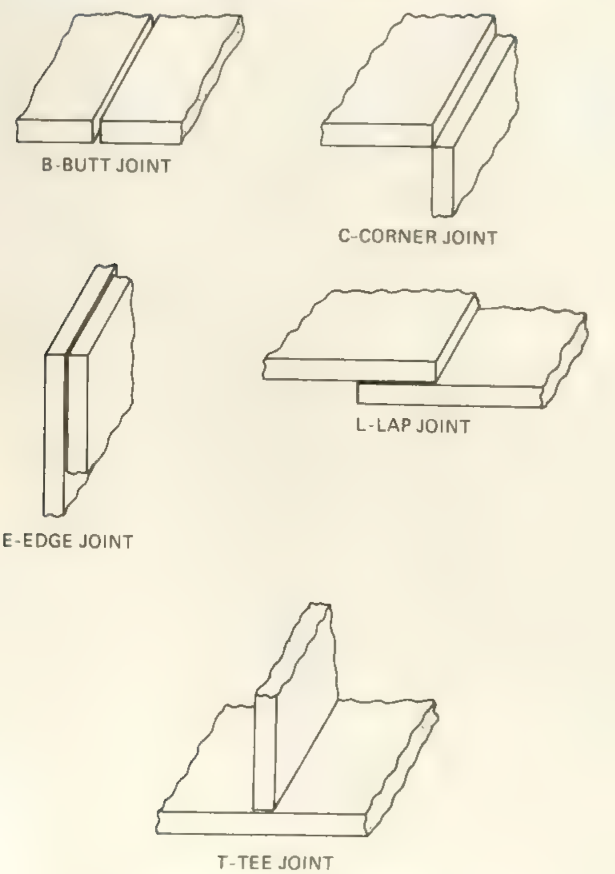
or few metal parts. A weldment may contain metals of different compositions and the pieces may be in the form of rolled shapes, sheet, plate, pipe, forgings, or castings. To produce a usable structure or weldment there must be weld joints between the various pieces that make the weldment. The **joint** is "the junction of members or the edges of members which are to be joined or have been joined." There are five basic types of joints for bringing two members together for welding. These joint types or designs are also used by other skilled trades.

The five basic joints (Figure 2-1) are:

- ☐ *B, Butt joint:* parts in approximately the same plane
- ☐ *C, Corner joint:* parts at approximately right angles and at the edge of both parts
- ☐ *E, Edge joint:* an edge of two or more parallel parts
- ☐ *L, Lap joint:* between overlapping parts
- ☐ *T, T joint:* parts at approximately right angles, not at the edge of one part

In making a weld, filler metal may or may not be used and heat with or without pressure is used, but the result is a continuity of solid metal.

FIGURE 2-1 Five basic joint designs.

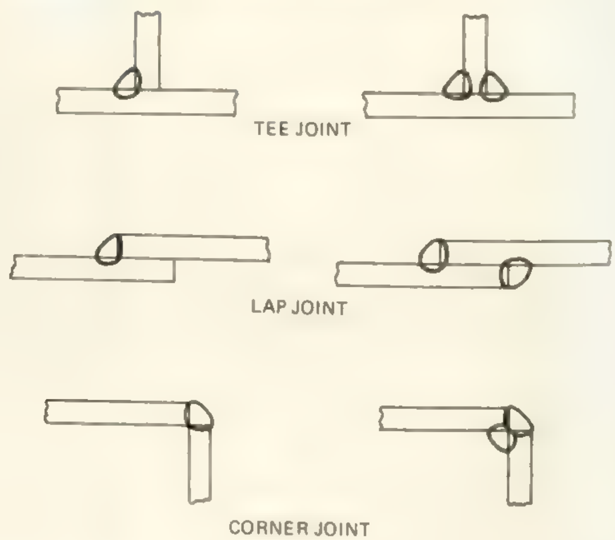


It is important to distinguish between the *joint* and the *weld*—each must be described to completely describe the **weld joint.** There are many different types of welds and they are best described by their shape when shown in cross section. The most popular weld is the **fillet weld,** named after its cross-sectional shape (Figure 2-2). The second most popular is the **groove weld** and there are seven basic types of groove welds (Figure 2-3). There are other types of welds: the **flange weld,** the **plug weld,** the **slot weld,** the **seam weld,** the **surfacing weld,** and the **backing weld.** Joints are combined with welds to make weld joints (Figure 2-4). Welds and joints are described completely in Chapter 19.

There are approximately 50 different distinct welding processes. They are subdivided into seven groups. The arc welding group of processes is the most popular and widely used for metal joining. There are nine distinct arc welding processes and numerous variations. In all of the arc welding processes, the heart of the welding system is the welding power source. This piece of equipment provides the electrical power to sustain the arc so that it can be used for making welds. There are many types, sizes, and variations. Some generate electricity from rotating energy sources, and are called welding generators. Others take the power available from the lines and change it to power suitable for arc welding. These are known as **transformers** or **rectifier welding machines.** Both alternating and direct current can be used for some of the arc welding processes. The welding process will determine the type of power source required.

The most important part of the welding system is the welder or welding operator, the human element. The difference between welders and welding operators is a difference of the manipulative skills involved. The welder must exercise skill and ability to manipulate equipment

FIGURE 2-2 Applications of single and double fillet welds.



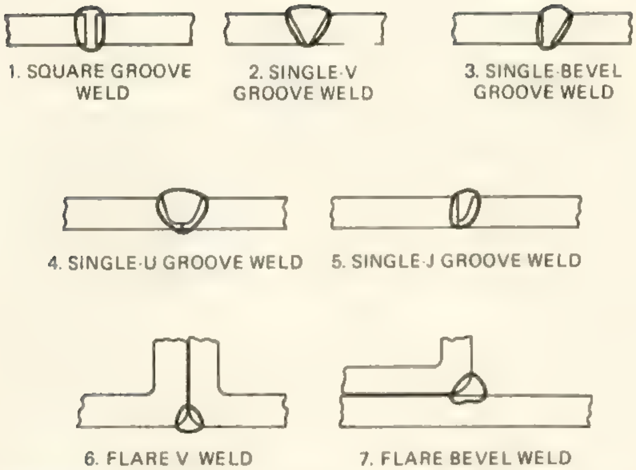


FIGURE 2-3 Seven basic groove welds.

to produce welds. The welding operator may monitor or operate an automatic welding machine.

Another way of dividing or categorizing welding processes relates to whether filler metal is or is not used. **Filler metal** is "the metal or alloy to be added in making a welded, brazed, or soldered joint." It becomes the weld fillet or weld metal in a groove weld. In some welding processes, the filler metal is carried across the arc and deposited in the weld. In others, filler metal is not carried across the arc but is melted by the heat of the arc and added to the molten puddle. If the weld metal passes through the arc, it is provided by an electrode. If it is melted by the heat of the arc and added to the pool, it is called a welding rod. Welding electrodes and welding rods have special composition requiring detailed specifications to describe them completely. Selection of filler metals is important; normally, their properties should match the properties of the metal being welded. This metal, called the **base metal**, is defined as "the material that is welded, brazed, soldered, or cut." This is the preferred term. In some countries the word base material or *parent* metal is used; for some processes the word *substrate* is used. The type of base metal often dictates the welding process that can be used.

To describe the making of a weld completely, it is necessary to specify the welding process to be employed and to state the method of applying the process. It is also necessary to describe the "welding procedure," which is the detailed method and practices involved in the production of a weldment. This should include materials, joint design details, and method of welding, in order to describe how a particular weld or weldment is to be made. It is becoming more and more important to describe and document the entire welding procedure completely.

To ensure that the welds conform to demanding specifications, specialized inspection techniques are used. These include destructive and nondestructive testing methods. Nondestructive testing includes visual inspection, magnetic particle inspection, radiographic inspection, liquid penetrant inspection, and ultrasonic inspection. Welding quality control is required by most codes and is a necessary requirement for most manufactured products.

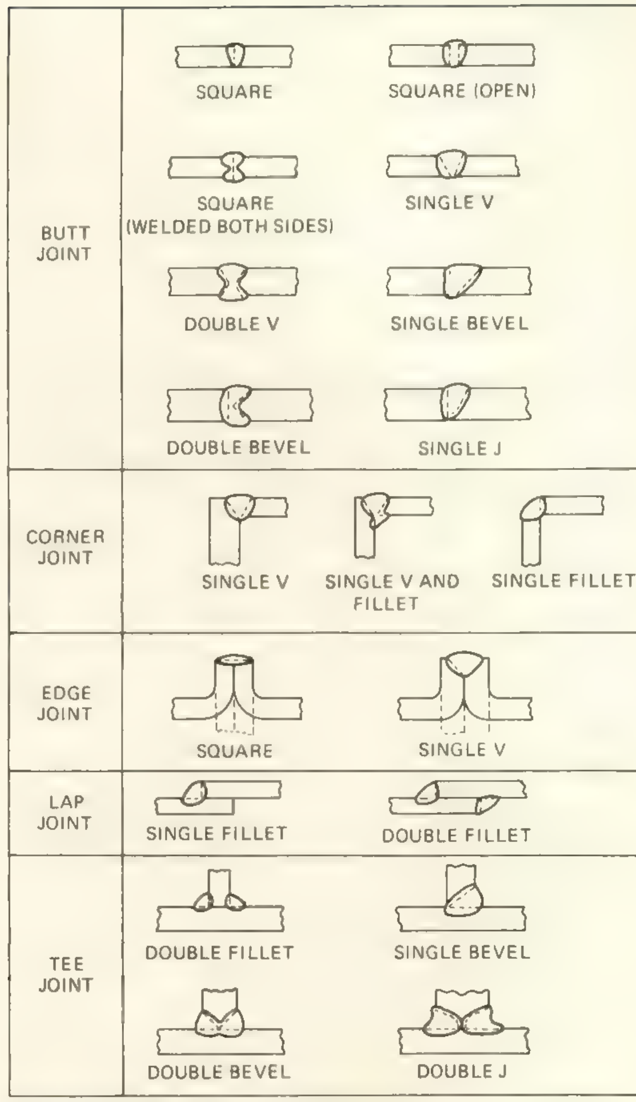


FIGURE 2-4 Some typical weld joints.

Welding is often done on structures in the position in which they are found. In view of this, techniques have been developed to allow welding in any position. Certain welding processes have "all-position" capabilities, while others may be used in only one or two positions. The welding positions are defined by the American Welding Society. There are four basic welding positions (Figures 2-5 to 2-7):

- *Flat:* the welding position used to weld from the up-

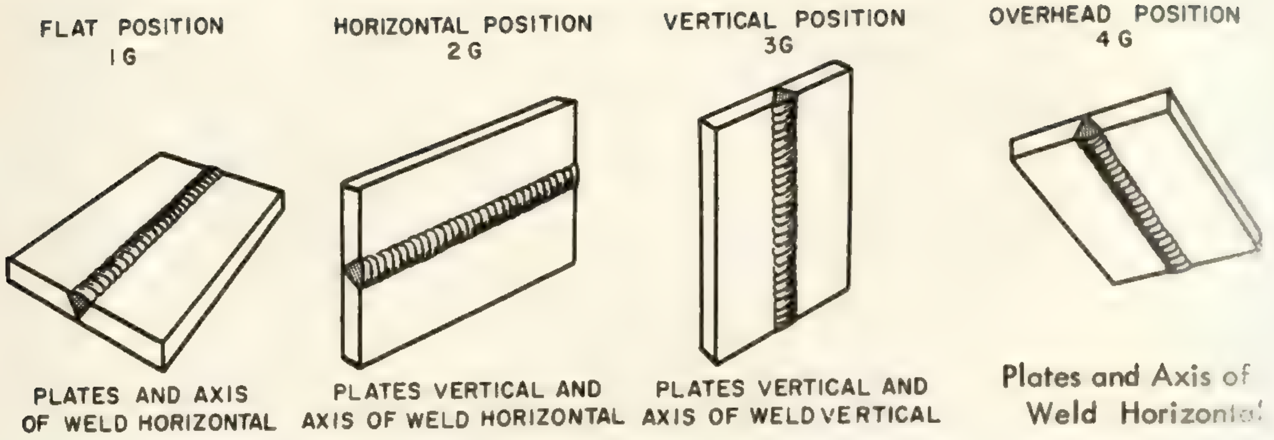


FIGURE 2-5 Welding positions for groove welds: plate.

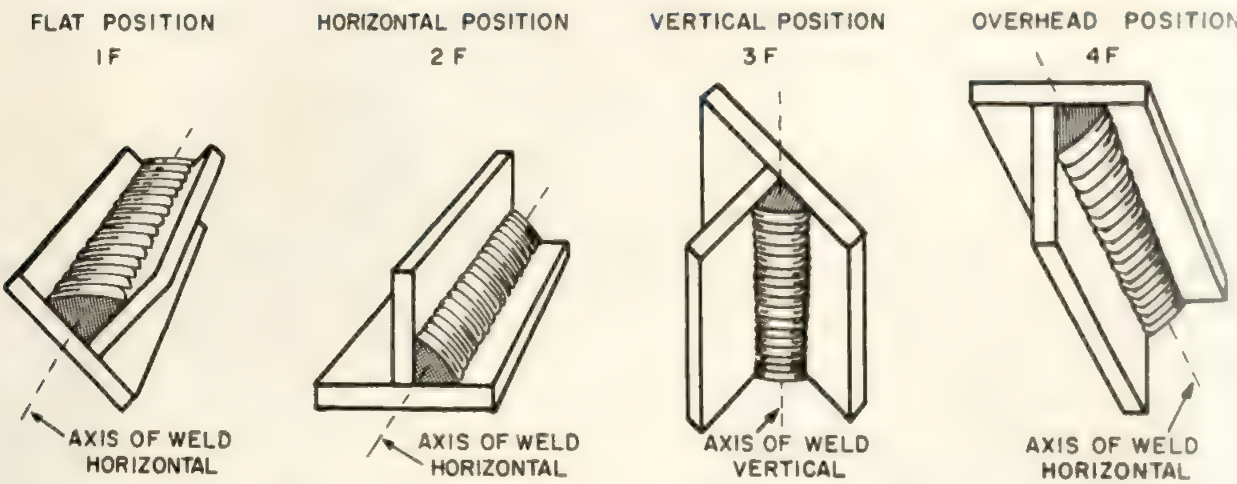


FIGURE 2-6 Welding positions for fillet welds: plate.

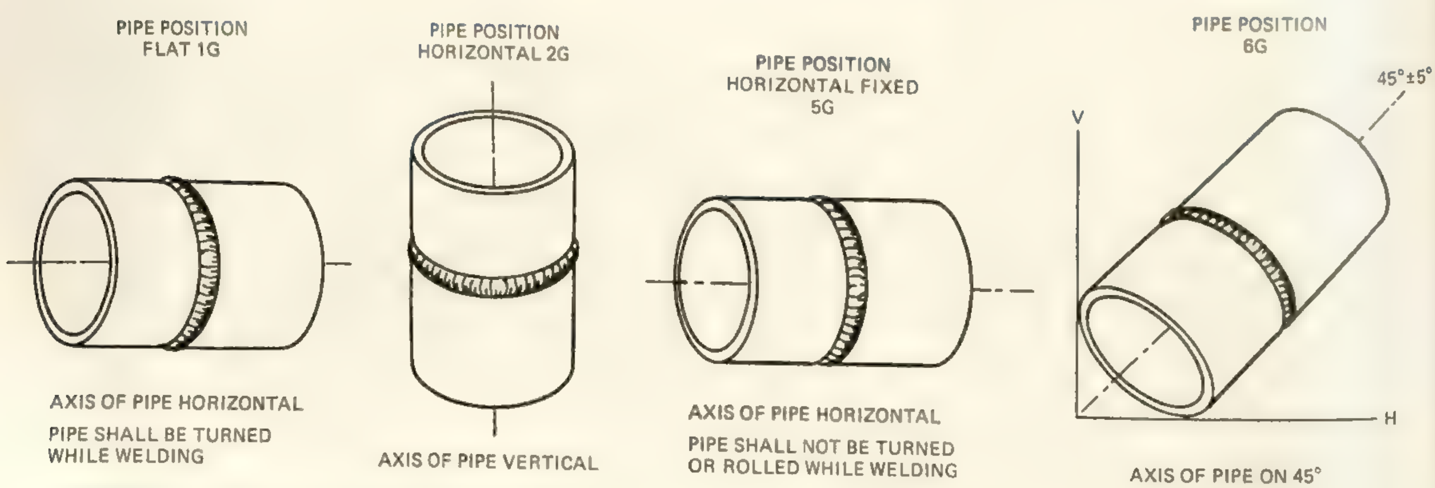


FIGURE 2-7 Welding positions for pipe welds.

per side of the joint; the weld face is approximately horizontal. **Flat welding** is the preferred term; however, this is sometimes called **downhand.**

- *Horizontal:* the position of welding in which the weld axis is approximately horizontal but the definition varies for groove and fillets.
- *Overhead:* the position in which welding is performed from the underside of the joint.
- *Vertical:* the position of welding in which the weld axis is approximately vertical.

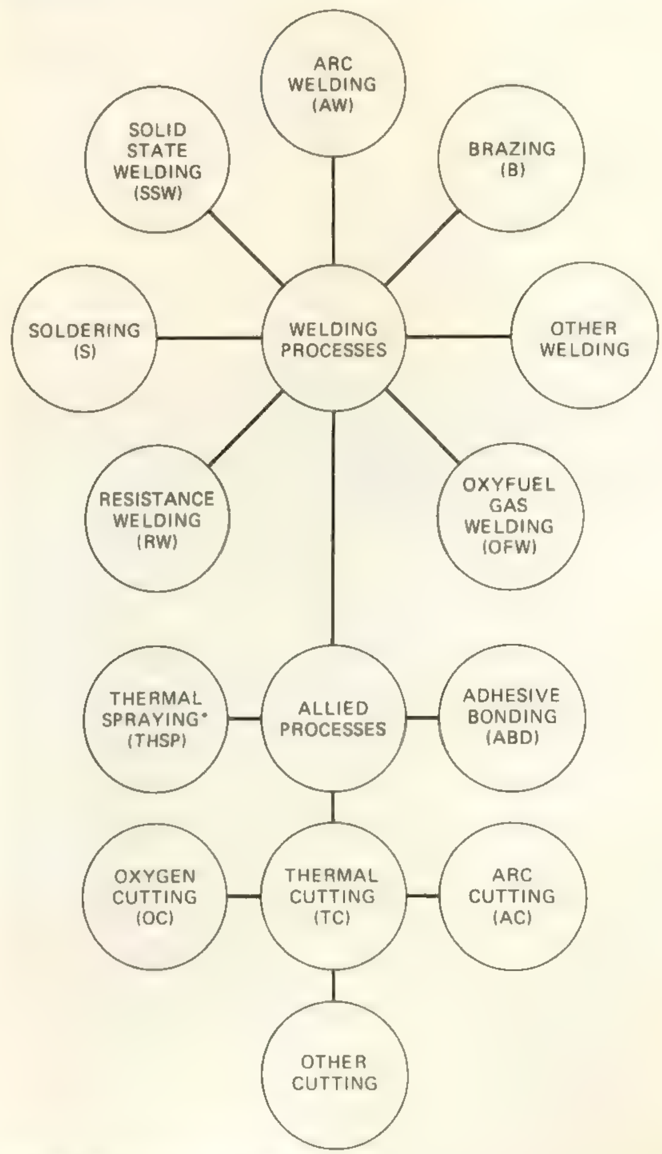
More terms and definitions will be presented in later chapters. It is important at the beginning to at least briefly define these terms so that you will better understand their meanings as you read further.

2-2 WELDING PROCESSES AND GROUPING

The American Welding Society has made each welding process definition as complete as possible so that it will suffice without reference to another definition. They define a process as "a distinctive progressive action or series of actions involved in the course of producing a basic type of result." The official listing of processes and their grouping is shown in Figure 2-8. The welding society formulated process definitions from the operational instead of the metallurgical point of view. Thus the definitions prescribe the significant elements of operation instead of the significant metallurgical characteristics. The definition for a welding process is "a joining process that produces coalescence of materials by heating them to the welding temperature with or without the application of pressure or by the application of pressure alone and with or without the use of filler material." AWS has grouped the processes together according to the "mode of energy transfer" as the primary consideration. A secondary factor is the "influence of capillary attraction in effecting distribution of filler metal" in the joint. Capillary attraction distinguishes the welding processes grouped under "brazing" and "soldering" from "arc welding," "gas welding," "resistance welding," "solid-state welding," and "other processes." The distinguishing feature of the latter groups of welding processes is the mode of energy transfer. "Adhesive bonding" is also included since it is being increasingly used to join metals.

The welding society deliberately omitted the designation of *pressure* or *nonpressure* since the factor of pressure is an element of operation of the applicable welding process. The designation "fusion welding" is not recognized as a grouping since fusion is involved with many of the processes. Other terms or factors such as the type of current used in arc or resistance welding processes, whether electrodes are *consumable* or *nonconsumable* or *continuous* or *incremental*, or the method of application are not shown in process groupings. These and other items characterize the methods by which the processes are performed. In some countries the welding processes are grouped differently; for example, in the United Kingdom group I is designated for welding processes using heat with pressure and group II is for welding processes requiring heat alone. In Germany, there is a distinction between pressure welding and fusion welding; the former includes ultrasonic, friction, forge, resistance, stud, and diffusion welding; the latter includes gas welding, electroslag welding, arc welding, plasma welding, electron beam and laser welding. Other countries refer to the type of energy involved: that is, thermochemical, electrothermic, mechanical energy, or focalized energy.

FIGURE 2-8 **AWS master chart of welding and allied processes.**



*SOMETIMES A WELDING PROCESS.

Welders sometimes distinguish between welds made with the addition of filler metal and those made by fusing only the joint edges together, an autogenous weld. However, it is best to relate to the welding process. Other ways of classifying are indicating the use of a nonconsumable or continuously fed electrode or the heat source, or by considering an exposed pool process versus nonexposed pool, which relates more to the skill of the welder. The AWS designation will be used throughout the book.

The arc welding processes are defined as "a group of welding processes that produce coalescence of work pieces by heating them with an arc. The processes are used with or without the application of pressure and with or without the use of filler metal." **Coalescence** is defined as a "growing together or growth into one body of the materials being welded," and is regarded as more applicable to all types of welding than the term *consolidation,* which might imply the use of external force or could mean bolting, riveting, nailing, and so on.

Arc Welding

The arc welding group includes nine specific popular processes, each separate and different from the others but in many respects similar. The arc welding group of processes is defined in the next few pages.

The **carbon arc welding** (CAW) process is the oldest of all the arc welding processes and is considered to be the beginning of arc welding. The welding society describes carbon arc welding as "an arc welding process that uses an arc between a carbon electrode and a weld pool. The process is used with or without shielding and without the application of pressure." Figure 2-9 shows the single carbon arc process in use. It has limited applications today, but a variation or twin carbon arc welding is more popular. Another variation uses compressed air for cutting and gouging steels. It is usually applied manually.

FIGURE 2-9 Carbon arc welding.

FIGURE 2-10 Shielded metal arc welding.

The development of the metal arc welding process soon followed the carbon arc. This developed into the currently popular **shielded metal arc welding** (SMAW) process, defined as "an arc welding process with an arc between a covered electrode and the weld pool. The process is used with shielding from the decomposition of the electrode covering, without the application of pressure, and with the filler metal from the electrode." Figure 2-10 shows this extremely popular process.

Automatic welding utilizing bare electrode wires was used in the 1920s, but it was the **submerged arc welding** (SAW) process that made automatic welding popular. Submerged arc welding is defined as "an arc welding process that uses an arc between a bare metal electrode and the weld pool. The arc and molten metal are shielded by a blanket of granular flux on the workpieces. The process is used without pressure and with filler

metal from the electrode and sometimes from a supplemental source." Submerged arc welding is shown in Figure 2-11. It is usually applied by machine or automatic methods; however, it can be applied semiautomatically. It is normally limited to the flat or horizontal position.

The need to weld nonferrous metals, particularly magnesium and aluminum, challenged the industry. A solution was found, called **gas tungsten arc welding** (GTAW), defined as "an arc welding process that uses an arc between a tungsten electrode (nonconsumable) and the weld pool. The processs is used with shielding gas and without the application of pressure. Filler metal may be added." The process developed in the late 1930s also became known as Heliarc or TIG welding and was immediately popular in the aircraft industry, where it was used to join "hard to weld" metals. GTAW welding is shown in Figure 2-12. Inert gases are used for shielding and are normally applied manually, although machine and automatic applications are becoming more popular.

A companion process was developed in the mid-1950s which is similar to gas tungsten arc except the arc is constricted to produce a plasma. It is called **plasma arc welding** (PAW), defined as "an arc welding process that uses a constricted arc between a tungsten electrode and the weld pool (transferred arc), or between the electrodes and the constricting nozzle (nontransferred arc). Shielding is obtained from the ionized gas issuing from the torch, which may be supplemented by an auxiliary source of shielding gas. The shielding gas may be an inert gas or mixture of gases. The process is used without the application of pressure." Plasma arc welding is shown in Figure 2-13. Filler wire, when it is used, is normally

FIGURE 2-11 Submerged arc welding.

FIGURE 2-12 Gas tungsten arc welding.

FIGURE 2-13 Plasma arc welding.

a "cold" or nonelectrical rod which is added to the molten puddle of the weld by the welder. Plasma welding has been used for joining some of the thinner materials. It is applied manually but also by machine and automatic methods. It is also popular as a cutting process.

Another welding process related to gas tungsten arc welding is known as **gas metal arc welding** (GMAW). It was developed in the late 1940s for welding aluminum and has become extremely popular. It is defined as "an arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of pressure." This process, sometimes called MIG welding, is shown in Figure 2-14.

The electrode wire for GMAW is continuously fed into the arc and deposited as weld metal. This process has many variations depending on the type of shielding gas, the type of metal transfer, and the type of metal welded. It is capable of welding many different metals and is becoming one of the most popular of the arc welding processes. The semiautomatic method of application is the most popular, but the process is also applied automatically.

A variation of gas metal arc welding which uses a different type of an electrode is known as **flux-cored arc welding** (FCAW). It is defined as "an arc welding process that uses an arc between a continuous filler metal electrode and weld pool. The process is used with shielding gas from a flux contained within the tubular electrode, with or without additional shielding from an externally supplied shielding gas, and without the application of pressure. This process is shown in Figure 2-15. It was developed in the mid-1950s. The coating material on the outside of a covered electrode is now included in the core or center of the tubular electrode wire. There are two variations; one utilizes external shielding gas and the other does not. Both are used primarily for welding steels and are applied by the semiautomatic and automatic method of application.

FIGURE 2-14 Gas metal arc welding.

FIGURE 2-15 Flux-cored arc welding.

A special application process within the arc welding group of processes is known as **stud arc welding** (SW). This process is defined as "an arc welding process that uses an arc between a metal stud, or similar part, and the other workpiece. The process is used with or without shielding gas or flux, with or without partial shielding from a ceramic ferrule surrounding the stud, with the application of pressure after the faying surfaces are sufficiently heated, and without filler metal." This process was developed in the mid-1930s. It is shown in Figure 2-16. There are several variations of the process and it is normally applied as an automatic or machine welding method.

A limited position welding process is a variation of the flux-cored arc welding process and the electroslag welding process and is known as **electrogas welding** (EGW). This is defined as "an arc welding process that uses an arc between a continuous flux-cored or solid electrode and the weld pool, employing vertical position

FIGURE 2-16 Stud welding.

FIGURE 2-17 Electroslag welding.

welding with molding shoes to confine the molten weld metal. The process is used with or without an externally supplied shielding gas, without the application of pressure, and filler metal is obtained from the electrode. There are two versions; one employs a solid electrode wire with externally supplied shielding gas, usually CO_2. The other variation uses a flux-cored electrode wire but without an externally supplied shielding gas. Both versions are applied as machine welding methods.

Electroslag welding (EW), a nonarc welding process, borrowed from the "other welding processes" group, is included here since it employs equipment used by the gas metal arc, flux-cored arc, submerged arc, and electrogas welding processes. It is defined as "a welding process that produces coalescence of metals with molten slag that melts the filler metal and the surfaces of the workpieces. The weld pool is shielded by this slag, which moves along the full cross section of the joint as welding progresses. The process is initiated by an arc that heats the slag. The arc is then extinguished by the conductive slag, which is kept molten by its resistance to electric current passing between the electrode and the workpieces. Molding shoes are used to confine the molten weld metal and slag. Pressure is not used." This process was invented in the early 1930s in the United States, but became popular when equipment was designed for its use in the Soviet Union in the early 1950s. There are two major variations, the upward-moving system and the consumable-guide system. The consumable-guide variation is shown in Figure 2-17. Electroslag welding is used normally to make welds in the vertical position and on steels. It is applied as a machine welding method.

Brazing

Brazing (B) is "a group of welding processes that produces coalescence of materials by heating them to the brazing temperature in the presence of a filler metal, having a liquidus above 450 °C (840 °F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary attraction." A braze is a very special form of weld; the base metal is theoretically not melted. There are seven popular different processes within the brazing group. The source of heat differs among the processes. Braze welding relates to welding processes using brass or bronze filler metal, where the filler metal is not distributed by capillary action.

Oxyfuel Gas Welding

Oxyfuel gas welding (OFW) is "a group of welding processes that produces coalescence of workpieces by heating them with an oxyfuel gas flame. The processes are used with or without the application of pressure and with or without the use of filler metal." There are four distinct processes within this group and in the case of two of them, *oxyacetylene welding* and *oxyhydrogen welding*, the classification is based on the fuel gas used. The heat

of the flame is created by the chemical reaction or the burning of the gases. In the third process, *air acetylene welding*, air is used instead of oxygen, and in the fourth category, *pressure gas welding*, pressure is applied in addition to the heat from the burning of the gases. This welding process normally utilizes acetylene as the fuel gas. The oxygen thermal cutting processes have much in common with the welding processes.

Resistance Welding

Resistance welding (RW) is "a group of welding processes that produces coalescence of the faying surfaces with the heat obtained from resistance of the workpieces to the flow of the welding current in a circuit of which the workpieces are a part, and by the application of pressure." In general, the difference of the resistance welding processes has to do with the design of the weld and the type of machine necessary to produce the weld. In almost all cases the processes are applied automatically since the welding machines incorporate both electrical control and mechanical functions.

Other Welding Processes

This group of processes includes those which are not best defined under the other groupings. It consists of the following processes: *electron beam welding, laser beam welding, thermit welding, induction welding, percussion welding,* and other miscellaneous welding processes, in addition to electroslag welding, which was mentioned previously.

Soldering

Soldering (S) is "a group of welding processes that produces coalescence of materials by heating them to the soldering temperature and by using a filler metal having a liquidus not exceeding 450°C (840°F) and below the solidus of the base metals. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary attraction." There are a number of different methods identified by the way heat is applied.

Solid-State Welding

Solid-state welding (SSW) is "a group of welding processes that produces coalescence of the faying surfaces by the application of pressure at temperatures below the melting point of the base metal without the addition of brazing or solder filler metal."

The oldest of all welding processes, *forge welding*, belongs to this group. Others include *cold welding, diffusion welding, explosion welding, friction welding, hot pressure welding, roll welding,* and *ultrasonic welding*. These processes are all different and utilize different forms of energy for making welds.

The welding processes, in their AWS official groupings, are shown in Figure 2-18 together with the letter

FIGURE 2-18 Popular welding processes and letter designations.

Group	Welding Process	Letter Designation
Arc welding	Carbon arc	CAW
	Electro gas	EGW
	Flux-cored arc	FCAW
	Gas metal arc	GMAW
	Gas tungsten arc	GTAW
	Plasma arc	PAW
	Shielded metal arc	SMAW
	Stud arc	[illegible]
	Submerged arc	SAW
Brazing	Diffusion brazing	[illegible]
	Dip brazing	DB
	Furnace brazing	[illegible]
	Induction brazing	[illegible]
	Infrared brazing	[illegible]
	Resistance brazing	[illegible]
	Torch brazing	[illegible]
Oxyfuel gas welding	Oxyacetylene welding	OAW
	Oxyhydrogen welding	OHW
	Air acetylene	
	Pressure gas welding	[illegible]
Resistance welding	Flash welding	[illegible]
	Projection welding	RPW
	Resistance seam welding	RSEW
	Resistance spot welding	RSW
	Upset welding	UW
Solid-state welding	Cold welding	CW
	Diffusion welding	DFW
	Explosion welding	EXW
	Forge welding	FOW
	Friction welding	FRW
	Hot pressure welding	HPW
	Roll welding	ROW
	Ultrasonic welding	USW
Soldering	Dip soldering	DS
	Furnace soldering	FS
	Induction soldering	IS
	Infrared soldering	IRS
	Iron soldering	INS
	Resistance soldering	RS
	Torch soldering	TS
	Wave soldering	WS
Other welding processes	Electron beam	EBW
	Electroslag	ESW
	Flow	FLOW
	Induction	IW
	Laser beam	LBW
	Percussion	PEW
	Thermit	TW

designation for each process. The letter designation assigned to the process can be used for identification on drawings, tables, and so on, and will be used throughout this book.

Allied and related processes include adhesive bonding, thermal spraying, and thermal cutting. These processes are described in Chapter 9.

2-3 METHODS OF APPLYING WELDING

Manual arc welding requires a high level of manipulative skill on the part of the welder. There is, however, more than one method of applying the different welding processes and some require very little manipulative skills. The title we use for the individual doing the welding indicates the manipulative skill level involved. By definitions: The **welder** is "one who performs a manual or semiautomatic welding operation." The **welding operator** is "one who operates machine or automatic welding equipment."

The definitions do not indicate the actual level of manipulative skill involved since both of them cover two methods of making welds. This tends to create confusion since a welder trained to do semiautomatic welding using one process may not be able to do manual welding with another process. This is not so important for the welding operator since the difference in skill for machine welding and automatic welding is not so great. The American Welding Society has established four specific methods of applying the many welding processes. These are based on the following interpretations:

- *Manual:* done, made, operated by, or used with the hand or hands.
- *Semiautomatic:* operated partly automatically and partly manually.
- *Machine:* mechanism serving to transmit and modify force and motion so as to perform some kind of work.
- *Automatic:* having a self-acting or self-regulating mechanism that performs a required act as a predetermined point in an operation.

The four methods of applying (Figure 2-19) are:

- *MA, Manual welding:* a welding operation performed and controlled completely by hand.
- *SA, Semiautomatic welding:* arc welding with equipment that controls only the filler metal feed. The advance of welding is manually controlled.
- *ME, Machine welding:* welding with equipment that performs the welding operation under the constant observation and control of a welding operator. The equipment may or may not load and unload the workpieces.
- *AU, Automatic welding:* welding with equipment that performs the entire welding operation without adjustment of the controls by a welding operator. The equipment may or may not load and unload the workpieces.

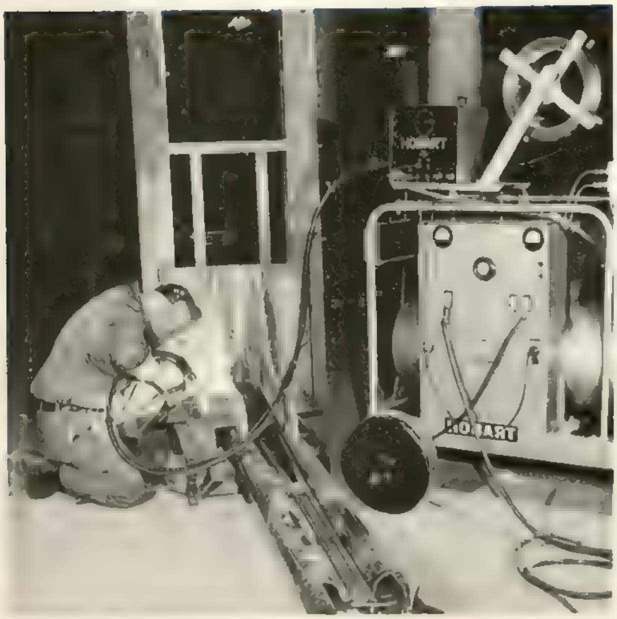
This concept of varying degrees of control in the hands of the welder can be better understood when we consider the normal activities involved when making an arc weld manually. These are defined and broken down into the following functions:

1. starts and maintains the arc. This includes holding and controlling the correct arc length.
2. feeds the electrode into the arc. This provides for filling the joint.
3. controls the heat for proper penetration.
4. moves the arc along the joint. This means providing relative travel or progression along the weld joint.
5. guides the arc along the joint, that is, following the joint and providing uniform fill or size.
6. manipulates the torch to direct the arc. This ensures fusion at the root and to previous weld beads.
7. corrects the arc to overcome deviations. This is to compensate for poor fit up, wide root openings, and so on.

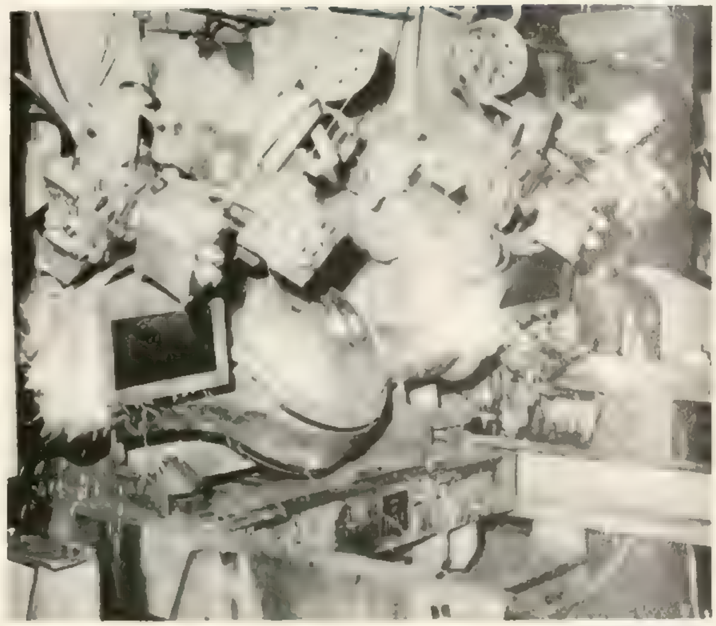
The person–machine relationship (Figure 2-19) shows that in manual welding the person has control over all of these functions and in automatic or automated welding the same functions are completely controlled by the machine. The skill required is greatest when all functions are under the control of the person and diminishes as the functions are taken over by the machine.

All of the arc welding processes can be analyzed with respect to the "method of applying." AWS uses these methods of applying also for brazing and oxygen cutting. The method of applying the resistance welding processes, solid-state welding processes, and most of the others is dictated by the process and the machine. Certain welding processes may be applied only as a manual process, while others are applied as semiautomatic, machine, or fully automatic. Figure 2-20 shows this relationship for some of the more popular processes. This figure also shows the processes where manipulative skills are normally involved. For these processes aptitude testing is suggested and skill training is required. The method of application is extremely important when writing procedures or assessing the economic capabilities of a process.

FIGURE 2-19 Individual-machine relationship related to method of applying arc welding.

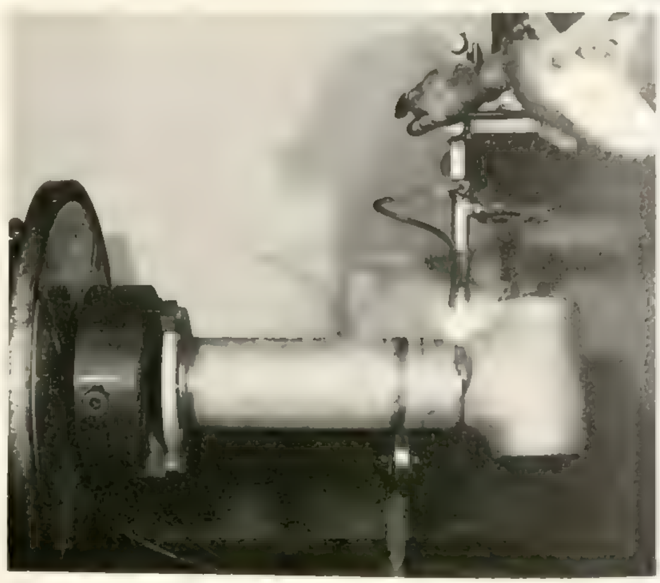


Semiautomatic



Automatic

Manual



Machine

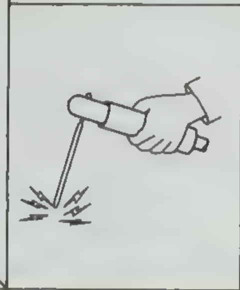
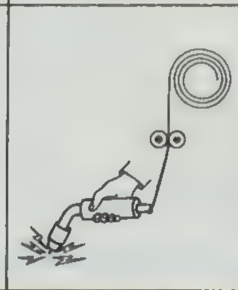
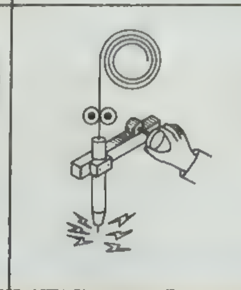
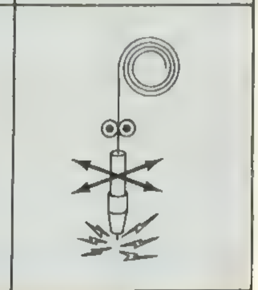
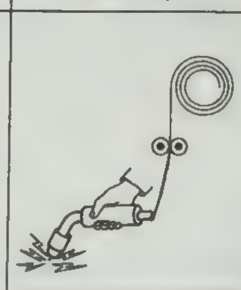
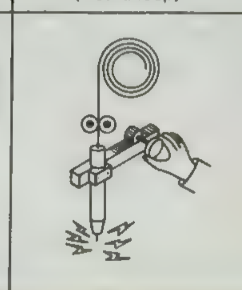
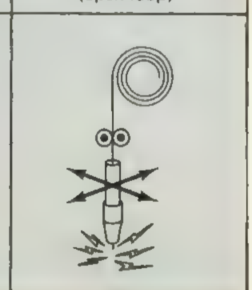
Arc Welding Elements/Function \ Method of Application	MA Manual (closed loop)	SA Semiautomatic (closed loop)	ME Machine (closed loop)	AU Automatic (open loop)
				
Starts and maintains the arc	Person	Machine	Machine	Machine
Feeds the electrode into the arc	Person	Machine	Machine	Machine
Controls the heat for proper penetration	Person	Person	Machine	Machine
Moves the arc along the joint (travels)	Person	Person	Machine	Machine
Guides the arc along the joint	Person	Person	Person	Machine via prearranged path
Manipulates the torch to direct the arc	Person	Person	Person	Machine
Corrects the arc to overcome deviations	Person	Person	Person	Does not correct, hence potential weld imperfections

FIGURE 2-19 *(Cont.)*

FIGURE 2-20 Possible methods of applying the various processes.

Welding or Cutting Process \ Method of Application	MA Manual (closed loop)	SA Semiautomatic (closed loop)	ME Machine (closed loop)	AU Automatic (open loop)
				
Gas metal arc[a]	Not possible	Most popular	Used	Popular
Flux cored arc[a]	Not possible	Most popular	Used	Popular
Gas tungsten arc[a]	Most popular	Possible-rare	Used	Used
Plasma arc[a]	Popular	Not used	Used	Used
Submerged arc	Not possible	Little used	Most popular	Popular
Stud	Not possible	Used	Used	Used
Electro gas	Not possible	Possible-rare	Most popular	Used
Shielded metal arc[a]	Most popular	Not used	Not used	Special
Carbon arc[a]	Most popular	Not used	Little used	Little used
Electroslag	Not possible	Possible-rare	Most popular	Used
Torch brazing[a]	Most popular	Used	Used	Used
Oxyfuel gas[a]	Most popular	Not used	Little used	Little used
Thermal cutting[a]	Most popular	Used	Popular	Popular

[a] Manipulative skills required for these processes when applied manually or semiautomatically.

2-4 WELDING PROCEDURES

As welding becomes an accepted engineering technology it requires that the elements involved be identified in a standardized way. This is accomplished by writing a procedure which is simply a "manner of doing" or "the detailed elements (with perscribed values or range of values) of a process or method used to produce a specific result." The AWS definition for a welding procedure is "the detailed methods and practices involved in the production of a weldment."

A welding procedure is used to make a record of all of the elements, variables, and factors that are involved in producing a specific weld or weldment. Welding procedures should be written whenever it is necessary to:

- □ Maintain dimensions by controlling distortion
- □ Reduce residual or locked-up stresses
- □ Minimize detrimental metallurgical changes
- □ Consistently build a weldment the same way
- □ Comply with certain specifications and codes

Welding procedures must be tested or qualified and they must be communicated to those who need to know. This includes the designer, the welding inspector, the welding supervisor, and last but not least, the welder.

When welding codes or high-quality work is involved, this can become a **welding procedure specification**, known as a WPS, which is "a document providing in detail the required variables for specific application to assure repeatability by properly trained welders and welding operators." Different codes and specifications may have somewhat different requirements for a welding procedure, but in general a welding procedure consists of three parts as follows:

1. A detailed written explanation of how the weld is to be made.
2. A drawing or sketch showing the weld joint design and the conditions for making each pass or bead.
3. A record of the test results of the resulting weld.

The variables involved in most specifications are considered to be essential variables. In some codes the term nonessential variables may also be used. Essential variables are those factors which must be recorded and if they are changed in any way, the procedure must be retested and requalified. Nonessential variables are usually of less importance and may be changed within prescribed limits and the procedure need not be requalified.

Essential variables involved in the procedure usually include the following:

1. The welding process and its variation
2. The method of applying the process
3. The base metal type, specification, or composition
4. The base metal geometry, normally thickness
5. The base metal need for preheat or postheat
6. The welding position
7. The filler metal and other materials consumed in making the weld
8. The weld joint, that is, the joint type and the weld
9. Electrical or operational parameters involved
10. Welding technique

Some specifications also include nonessential variables and these are usually the following:

1. Travel speed
2. The travel progression (uphill or downhill)
3. The size of the electrode or filler wire
4. Certain details of the weld joint design
5. The use and type of weld backing
6. The polarity of the welding current

The procedure write-up must include each of the listed variables and describe in detail how it is to be done. The second portion of the welding procedure is the joint detail sketch and table or schedule of welding conditions.

Tests are performed to determine if the weld made to the welding procedure specification (WPS) meets the standards described by the code or specification. If these tests meet the minimum requirements, the document becomes the **welding procedure qualification record** (WPQR). This is a record of welding variables used to produce an acceptable test weldment, and the results of tests conducted on the weldment qualify a welding procedure specification. The writing, testing, and qualifying procedures become quite involved and may be different for different specifications. This is covered in detail in Chapter 21.

In certain codes, welding procedures are prequalified. By using data provided in the code, individual qualified procedure specifications are not required for the standard joints on common base materials using the shielded metal arc welding process.

The factors included in a procedure should be considered in approaching any new welding job. By means of knowledge and experience establish the optimum factors or variables in order to make the best and most economical weld on the material to be welded and in the position that must be welded.

Welding procedures take on added significance based on the quality requirements that can be involved. When exact reproducibility and perfect quality are required, the procedures will become much more technical with added requirements, particularly in testing. Tests will become more complex to determine that the weld joint has the necessary properties to withstand the service for which the weld is designed.

Procedures are written to produce the highest-quality weld required for the service involved, but at the least possible cost and to provide weld consistency. It may be necessary to try different processes, different joint details, and so on, to arrive at the lowest-cost weld that will satisfy the service requirements of the weldment.

The contents of a welding procedure are brought out at this early stage to help you realize the importance of defining the factors involved in making a successful weld.

2-5 WELDING ELECTRICITY

The electrical arc welding circuit is the same as any electrical circuit. In the simplest electrical circuits, there are three factors:

Current: flow of electricity

Pressure: force required to cause the current to flow

Resistance: force used to regulate the flow of current

Current is a "rate of flow." Current is measured by the amount of electricity that flows through a wire in one second. One *ampere* (A) is the amount of current per second that flows in a circuit. The letter *I* is used to designate current in amperes.

Pressure is the force that causes a current to flow. The measure of electrical pressure is the *volt.* The voltage between two points in an electrical circuit is called the *difference* in potential. This force or potential is called *electromotive force* (EMF). The difference of potential or voltage causes current to flow in an electrical circuit. The letter *E* is used to designate voltage or EMF.

Resistance is the restriction to current flow in an electrical circuit. Every component in the circuit, including the conductor, has some resistance to current flow. Current flows easier through some conductors than others; that is, the resistance of some conductors is less than others. Resistance depends on the material, the cross-sectional area, and the temperature of the conductor. It is designated by the letter *R*. The unit of electrical resistance is the *ohm*. Copper is widely used for conductors since it has the lowest electrical resistivity of common metals. Insulators have a very high resistance and will not conduct current.

The simple electrical circuit shown in Figure 2-21 includes two meters for electrical measurement, a voltmeter, and an ammeter. It also shows a symbol for a battery. The longer line of the symbol represents the positive terminal. Outside of a device that sets up the EMF, such as a generator or a battery, the electron current flows from the negative (−) to the positive (+). The arrow shows the direction of current flow.

The ammeter is a low-resistance meter, shown by the round circle and arrow adjacent to the letter *I*. The pressure or voltage across the battery can be measured by a voltmeter. The voltmeter is a high-resistance meter, shown by the round circle and arrow adjacent to the letter *E*.

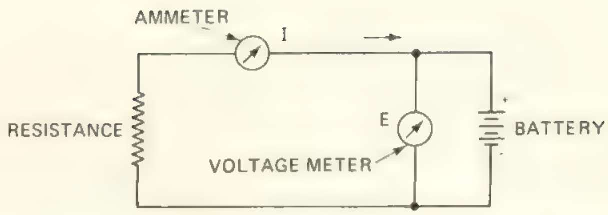


FIGURE 2-21 Simple electrical circuit.

The resistance in the circuit is shown by a zigzag symbol. The resistance of a resistor can be measured by an ohmmeter. An ohmmeter is *never* used to measure resistance in a circuit when current is flowing.

The relationship of these three factors is expressed by *Ohm's law* as follows:

$$\text{current} = \frac{\text{pressure}}{\text{resistance}}$$

or

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}} \quad \text{or} \quad I = \frac{E}{R}$$

where I = current in amperes (flow)
E = pressure in volts (EMF)
R = resistance in ohms

Ohm's law can also be expressed as

$$E = IR \quad \text{or} \quad \text{R} = \frac{E}{I}$$

By simple arithmetic, if two values are known or measured, the third value can be determined.

A few changes to the circuit can be made to represent an arc welding circuit. Replace the battery with a welding generator since they are both a source of EMF (or voltage) and replace the resistor with a welding arc, which is also a resistance to current flow (Figure 2-22). The electron current will flow from the negative terminal through the resistance of the arc to the positive terminal.

In the early days of arc welding, using bare metal electrodes, it was normal to connect the negative side of the generator to the electrode and the positive side to the workpiece. This was known as **straight polarity** and is shown in Figure 2-22. When deeper penetration was required on the base metal, the polarity would be **reversed.** This connected the electrode to the positive pole of the generator and the workpiece to the negative pole. In the

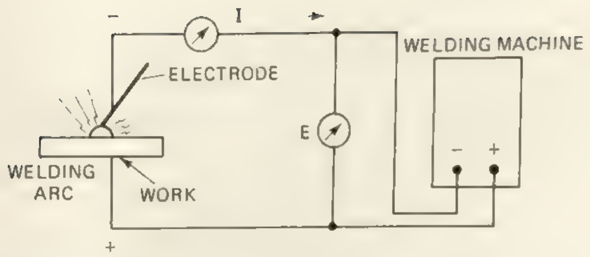


FIGURE 2-22 Welding electrical circuit (straight polarity).

arc, more heat is liberated at the negative pole; hence when the electrode is negative, it melts off faster, and when the workpiece is negative, deeper penetration results.

In those days, to change the polarity it was necessary to remove the cables from the machine terminals and replace them in the reverse position. The early coated electrodes for welding steel gave best results with the electrode positive or reverse polarity; however, bare electrodes were still used. It was necessary to change polarity frequently when using both bare and covered electrodes.

To meet this condition, welding machines were equipped with switches that changed the polarity of the terminals and with dual reading meters. Thus the welder could quickly change the polarity of the welding current. In marking welding machines and polarity switches these old terms were used and indicated the polarity as *straight* when the electrode is negative, and *reverse* when the electrode is positive. In this book, to avoid confusion, whenever polarity is discussed the term **electrode negative** (DCEN) is used instead of "straight polarity" (DCSP) and **electrode positive** (DCEP) is used instead of "reverse polarity" (DCRP).

The ammeter used in a welding circuit is a millivoltmeter calibrated in amperes connected across a high current shunt in the welding circuit. The shunt is a calibrated, very low resistance conductor. The voltmeter shown in the figure will measure the welding machine output and the voltage across the arc which are essentially the same. Before the arc is struck or if the arc is broken, the voltmeter will read the voltage across the machine with no current flowing in the circuit. This is known as the *open-circuit voltage* and is higher than the arc voltage or voltage across the machine when current is flowing.

Another unit in an electrical circuit, and important to welding, is the unit of *power*. The rate of producing, or of using, energy is called power and is measured in watts. Power in a circuit is the product of the current in amperes times the pressure in volts, or

$$\text{power} = \text{current} \times \text{pressure}$$

or

$$\text{watts} = \text{amperes} \times \text{volts}$$

or

$$P = I \times E$$

where P = power in watts
I = current in amperes
E = pressure in volts

When welding using a ¼-in. electrode at 100 amperes and an arc voltage of 25, the power would be 2500 watts (W); 2500 W can be expressed as 2.5 kilowatts (kW). Power is measured by a wattmeter, which is a combination of an ammeter and a voltmeter.

In addition to power, it is necessary to know the amount of work involved. Electrical *work* or energy is the product of power times time and is expressed as watt-seconds or joules or kilowatt-hours.

$$\text{work} = \text{power} \times \text{time} \quad \text{or} \quad W = Pt$$

where W = work in watt-seconds or joules or kilowatt-hours
P = power in watts or kilowatts
t = time in seconds or hours

Cost-of-welding calculations involve these work units since the watt-hour or kilowatt-hour are commercial units of work and are the basis of charges by the electric utility companies.

So far, we have dealt exclusively with direct current electricity, electricity that flows continually through the circuit in the same direction. Alternating current electricity is also important since it is the power furnished by utility companies.

Alternating current is an electrical current which flows back and forth at regular intervals in a circuit. When the current rises from zero to a maximum, returns to zero and increases to a maximum in the opposite direction, and finally returns to zero again, it is said to have completed one cycle. For convenience, a cycle is divided into 360 degreees. Figure 2-23 is a graphical representation of a cycle and is called a *sine wave*. It is generated by one revolution of a single loop coil armature in a two-pole alternating-current generator. The maximum value in one direction is reached at the 90° point and in the other direction at the 270° point. The number of times this cycle is repeated in one second is called the frequency and is measured in hertz. When a current rises to a maximum in each direction 60 times a second it completes 60 cycles per second or has a frequency of 60 hertz (Hz). The frequency of electrical power in North America and other parts of the world is 60 hertz. Fifty hertz is used in Europe, Africa, most of Asia, and South America.

The principle of electrical generation states that "when a conductor moves in a magnetic field so as to

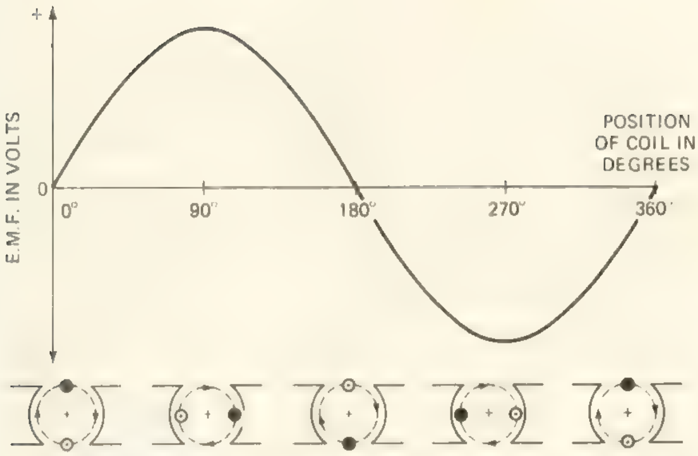


FIGURE 2-23 Sine-wave generation.

cut lines of force an electromotive force is generated." The lines of force run between the north and south magnetic poles of the generator. The single turn coil rotates within these lines of force or magnetic field and as the conductor cuts the lines of force at right angles the maximum voltage is generated (i.e., at 90° and at 270°). When no lines of force are being cut as at positions 0°, 180°, and 360°, there is no EMF generated. The EMF generated in the one loop coil is taken from the rotating armature by means of slip rings. In welding generators there are usually more than two poles and many hundred loops of wire in the coil.

Alternating current (ac) for arc welding normally has the same frequency as the line current. The voltage and current in the ac welding arc follow the sine wave and go through zero twice each cycle. The frequency is so fast that the arc appears continuous and steady to the naked eye. The sine wave is the simplest form of alternating current. It is always assumed that alternating current has a sine wave shape unless otherwise stated.

Alternating current and voltage are measured with ac meters. An ac voltmeter measures the value of both the positive and negative parts of the sine wave. It reads the effective voltage, called the root-mean-square (rms) voltage. The effective direct-current value of an alternating current or voltage is 0.707 times the maximum value.

An alternating current has no unit of its own, but is measured in terms of direct current, the ampere. The ampere is defined as a steady rate of flow, but an alternating current is not a steady current. An alternating current is said to be the equivalent to a direct current when it produces the same average heating effect under exactly similar conditions. This is used since the heating effect of a negative current is the same as that of a positive current. Therefore, an ac ammeter will measure a value called the effective value of an alternating current which is shown in amperes. All ac meters, unless otherwise marked, read effective values of current and voltage.

Ohm's law also applies to alternating-current circuits. This is because Ohm's law deals only with voltage, current, and resistance. In alternating-current welding circuits there are other factors, and one of the most important is inductance. To understand inductance we must refer to magnetism.

A magnet has a north pole and a south pole, which have identical strength. Between these poles there are lines of force. This effect can be shown by sprinkling iron filings on a sheet of paper and placing it over a magnet. The distinct pattern shows these lines of force running from one pole to the other. Similar lines of force exist around electric conductors that carry direct current. This can be proven by placing a small compass near a current-carrying wire. The needle will deflect when the current is turned off and on. Magnetic lines of force create physical forces between magnets or magnetic fields around current-carrying wires. This is the principle of operation of an electric motor. The magnetic properties of a ferromagnetic material such as iron when wrapped with a coil of wire are such that the combination will produce a much stronger magnetic field than the magnetic field produced by the coil alone. The coil of wire around an iron core is a magnetic circuit. Magnetic circuits will have a specific inductance. Inductance expresses the results of a certain arrangement of conductors, iron, and magnetic fields. Inductance involves change since it functions only when magnetic lines of force are cutting across electrical conductors. Inductance is important only in alternating current circuits or in direct-current circuits when they are connected or disconnected. When the current is turned off, the magnetic field collapses and the lines of force cut across the wires and induce current in the wires in the same direction as it had been flowing. If the coil is connected to alternating current the lines of force build up to the maximum and then collapse and then build up in the opposite direction to a maximum and collapse each cycle. If another coil is placed on the same iron core and close to the first coil the magnetic lines of force will cut across the second coil and induce the EMF in it. The closer the coils, or the stronger the magnetic lines of force, the greater will be the induced EMF. This is the principle of the transformer and is shown in Figure 2-24. By changing the magnetic coupling of the two coils we can control the output of the second coil (the secondary) and thus the output of the welding transformer. This coupling can be changed by moving the coils closer together or by increasing the strength of the magnetic field between them. The strength of the magnetic field can be changed by putting more or less iron in the area between the coils or by adjusting the availability of the magnetic field in other ways.

The output of a transformer welding machine is alternating current of the same frequency as the input power. A rectifier is a device that conducts current easier

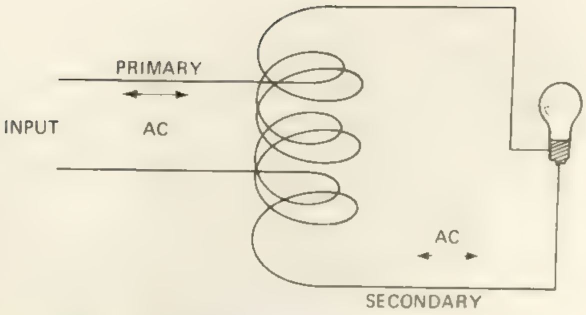


FIGURE 2-24 Transformer principle.

in one direction than the other. It has a high resistance to current flowing in one direction and a low resistance to current flowing in the opposite direction. A diode vacuum tube is an efficient rectifier but will not carry sufficient current for welding. Another type, the dry disk rectifier, employs layers of semiconductors such as selenium between plates. The newest and most popular rectifier is the silicon diode. These are made of thin wafers of silicon that have had small amounts of impurities added to make them semiconductors. The wafers are specially treated and then assembled in holders for mounting in welding machines. The diodes are connected to the output of a welding transformer to produce a rectifier welding machine with dc output.

This brief discussion of electricity is presented to help explain the electricity of welding. More about welding electricity will be given in later chapters.

2-6 WELDING PHYSICS AND CHEMISTRY

Welding follows all the physical laws of nature, and a good understanding of physics and chemistry will help you better understand how welds are made. Physics deals with energy and motion and is subdivided into such subjects as mechanics, sound, light, friction, magnetism, electricity, heat, and so on. This section briefly describes some of these subjects.

The science of mechanics involves physical laws that relate to forces, motion, and direction. The term **force** is defined as a push or pull; specifically a force is a tendency to produce a change, a change in motion of the body upon which it acts. It is not necessary that the body be in motion; it is only necessary that there is a tendency to produce change. The first law of motion states that a body will remain at rest or in uniform motion, if no force acts upon it. One of the forces that we live with daily is the pull of gravity, which acts on all objects on the earth's surface. Another of the laws states that for every action there is an equal and opposite action; that is, forces act in pairs. An opposite action force cannot exist before the action force takes place. If you push against the wall, the wall pushes back an equal and opposite force equal to your push; otherwise the wall would move. All forces and all opposite forces or reaction forces have direction and also have **magnitude**, which is the amount of force involved. It is possible to graphically represent different forces and magnitudes and direction by means of vector diagrams. Vectors indicate the direction, and the length of the vector indicates the magnitude. A thorough knowledge of this science is necessary in order to design welded structures. It is the basis for establishing the sizes of members and would be the basis for the size of welds to join members together.

The science of sound is important to welding since one welding process and one nondestructive examination technique are based on the use of sound. Sound is transmitted through most materials: metals, gases, liquids, and so on, but it will not pass through a vacuum. Sound is an alternating type of energy based on vibrations, which are regions of compaction and rarification. A compression wave and rarification wave are alternating pressures or vibrations which allow your eardrums to hear. The hearing of most people is sensitive between 20 and 20,000 vibrations per second. Sound has pitch, loudness, and quality. *Pitch* is defined as frequency; the higher the frequency, the higher the pitch. *Loudness* is subjective and is related to intensity, which is the basis of the energy in sound. *Quality* is the function of waveform based on the frequency and phase of combining vibrations. The use of sound in welding is in the higher-than-audible sound vibrations, above the normal hearing range for people. Ultrasonic vibrations are used to make welds and they are also used to detect voids in metals.

The frequency spectrum shown in Figure 2-25 is of interest when studying welding. This figure shows the spectrum from the lowest frequency and the longest wavelength to the highest frequency with the shortest wavelength and covers both the sonic and the electromagnetic spectrum. Sonic frequencies are at the low end and, having a relatively low travel speed, must travel through some type of media. Electromagnetic radiation travels at the speed of light and will travel through a vacuum and is normally in the higher-frequency range.

Sonic radiation includes the audio frequencies, which we normally hear, and the ultrasonic range frequencies, higher than the normal hearing range of people. The upper range for adults is normally from 15 to 17 kilohertz (kHz). Children have the ability to hear higher frequencies; dogs and some other animals can hear frequencies even higher. The musical scale ranges from below 20 Hz to over 4000 Hz, with middle C 261 Hz. The speed of travel of sound is the slowest through gases, which is approximately 200 meters per second (m/sec). It travels faster through liquids, ranging from approximately 1000 m/sec to almost 2000 m/sec and has the highest speed through solids, ranging from 1000 to over 4000 m/sec in nonmetals and as high as 10,000 m/sec

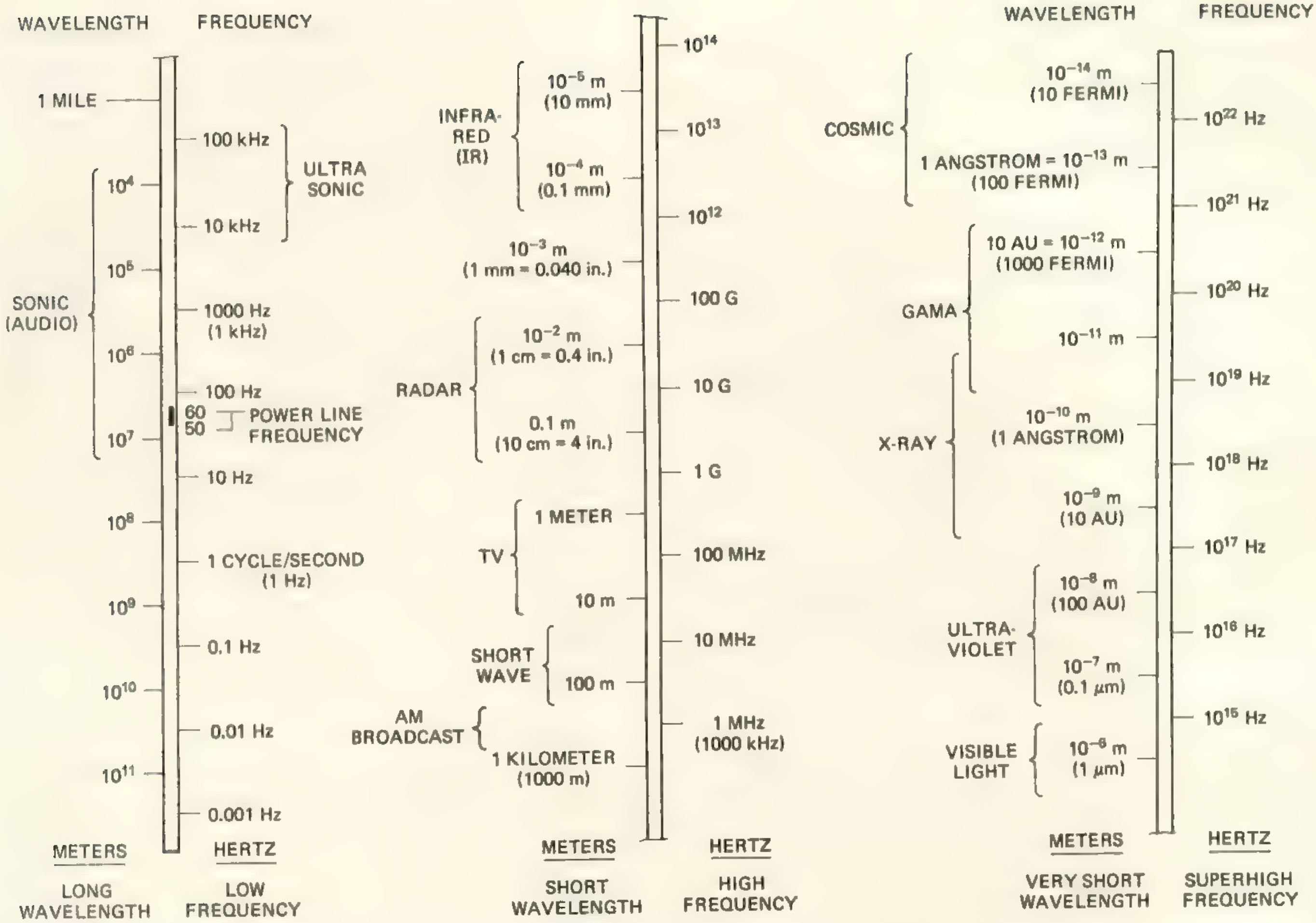


FIGURE 2-25 **Frequency spectrum for sonic and electromagnetic radiation.**

through metals. The rate is different for different metals. It is also different through liquids at different temperatures, traveling faster at lower temperatures. The pulsing rates used in welding and the frequency used in ultrasonic testing are in these ranges.

The electromagnetic frequency spectrum is much larger and includes radio broadcasting frequencies up through the infrared frequencies, visible light, x-rays, and gamma rays. Electromagnetic frequencies travel approximately 186,000 miles per second in air or vacuum, but change to a slower speed when going through liquids or transparent solids. The high-frequency current used for arc starting in gas tungsten arc welding is in the range of approximately 2 megahertz. The frequency of power-line alternating current is 60 Hz in North America and 50 Hz in many other parts of the world. It is important to keep these numbers in perspective since they vary over such a wide range. A study of Figure 2-25 will give you a better idea of the frequencies involved in different aspects of welding and weld testing.

The science of light also involves welding. The laser beam welding process utilizes light energy at very high concentrations to create heat sufficient to cause melting, which can be used for welding or cutting. Light is a by-product of the arc welding processes. Light is given off by the arc and by heated electrodes and base metals. Light is a phenomenon that has never been completely explained to the satisfaction of scientists. Propagation of light is explained by alternating vibrations or the wave theory, while the energy transfer of light is explained by the particle theory. It is sufficient for us to know that light is transmitted through vacuums and gases, but not through all types of materials. Light is of interest to the welder from the point of view of protecting the body from the effects of the light rays. In the electromagnetic spectrum, light ranges from the lower frequencies of infrared through visible light up through the ultraviolet and x-rays. The speed of light is independent of the light source, its intensity, or color. Light transmits energy, and the higher the frequency, the greater the energy; however, light radiates equally in all directions and its strength diminishes by the square of the distance.

The science of friction also involves welding. Here we are interested in dynamic friction, better known as *sliding friction*. This is the force between two moving bodies and if sufficient force is available heat will be

generated. This is the basis for the friction-welding process.

The magnetic theory and its relationship to current flow are explained in the section on welding electricity. One aspect of magnetic fields can be detrimental. Welders call it arc blow, which is the deflection of an electric arc from its normal path due to magnetic forces. The leads from the welding machine to the electrode, and from the work back, carry a heavy current and create a magnetic field. The welding current flowing through the electrode and the base metal, providing it is ferromagnetic, also creates magnetic fields. The intensity of the magnetic field is directly proportional to the square of the current flowing. The distribution of a magnetic field in a welding circuit can become quite complex, particularly for non-uniform joint details and also when fixtures are employed. If the distribution of the magnetic field close to the arc is not uniform, it may cause the arc to deflect or attract toward the stronger portion, depending on polarity. Arc blow can create difficulties which affect weld quality. One advantage of alternating current is that the arc blow is minimized since the magnetic field is changing at line frequency and does not build up to as great a force.

Chemistry deals with the makeup of all matter. We are most interested in metals in connection with welding. By definition, matter is anything that occupies space and has mass or weight. Also by definition, elements are those particular kinds of matter which cannot be decomposed or broken down into simpler substances by ordinary means. Pure metals and pure gases are examples of elements. Compounds or mixtures can be broken down into their original elements. The elements are composed of atoms which are identical with each other atom of the same element but are different from atoms of other elements. The molecule is the smallest particle of a substance which has all the properties of that substance. It is a combination of two or more atoms of the same element or of different elements.

Many of the elements have similar properties; for example, some are inert gases, others are noble metals, others are active gases, etc. This allows the elements to be classified and put into groups of families. This classification is called the *periodic table*, which is shown in all chemistry textbooks.

To better understand metals, we must first consider the atom and its structure. Scientists believe that each atom is composed of a very small compact nucleus surrounded by empty space in which one or more electrons revolve about the nucleus. It is believed that the nucleus of the atom is the most dense form of matter known. It is made or contains two main types of particles known as protons and neutrons. These particles differ from each other in their charge, but they have about the same weight. The positive particle of matter is called a proton. All atoms have at least one proton in their nuclei. The number of protons in the nucleus is equal to the number of electrons outside the nucleus. Each proton has a charge of plus one; the charge on the nucleus is positive since it contains positively charged protons and no electrons. The neutron in the nucleus is a particle of matter which has a relative weight of 1 but it has no electrical charge. The third item is the electron and it is very light in comparison with the nucleus of the atom. Each electron has a charge of negative 1. Electrons of an atom are located in shells around the nucleus. These shells are more properly called energy levels because electrons in different shells have different amounts of energy. Electrons revolve around the nucleus in these shells in varying distances from the nucleus. Electrons are relatively far from the nucleus so that most of the atom consists of *empty space*. The difference between atoms of different elements is the result of differences in the number of protons and neutrons in the nucleus and the difference in the number and arrangement of the electrons surrounding the nucleus. Electrons in the outer shells have more energy than those in the inner shells. An electron can change from one shell or energy level to another; if it absorbs energy it moves to an outer shell or to a higher energy level. If it gives off energy it drops to a shell closer to the nucleus. Energy emitted when electron drops from a higher to a lower energy level is in the form of electromagnetic radiation, light, or x-rays. The study of the makeup of the atoms is extremely technical and beyond the scope of this book. However, this brief explanation will help you better understand the makeup of metals, which will be explained further later.

Matter can exist in four states: solids, liquids, gases, and plasmas. Changes from one state to another are brought about by supplying energy in the form of heat. Water in the solid state is ice; by adding heat, the ice changes to water, which is its liquid state, and by adding additional heat, will be converted to its gaseous state. The reverse can be done by removing heat energy and the gas (steam) turns to the liquid (water) and then to the solid (ice). Most substances can be changed from one physical state to another in the same manner. The temperature of these changes indicates the physical state the element will be at the normal room temperatures.

Each of the elements on the periodic table has its own name and symbol. Most of these elements will combine chemically to form compounds. There is the law of definite composition, which states that a chemical compound always contains the same elements with the same ratio of atoms of each. This is not true for mixtures. Most commercial metals are mixtures or alloys in that they are predominantly the element of the pure metal plus additions of other elements but not chemically combined as a compound. Gases also occur as elements, compounds, or mixtures. Air is a mixture of approximately 78% nitrogen and 20% oxygen with small amounts of other elements. Carbon dioxide is a compound and always in

the ratio of one atom of carbon and two atoms of oxygen. Argon is an element and more importantly an inert gas which will not chemically combine with any other element.

Several other chemical definitions relate to welding. One is known as burning or oxidation. This takes place when any substance combines with oxygen usually at high temperatures. An example of this is the combining of acetylene with oxygen. This produces carbon dioxide plus water plus a large amount of heat. We use the heat produced by the burning of acetylene in the flame of the oxyacetylene torch to make welds. In all oxidation reactions heat is given off. Oxidation can occur very slowly as in the case of rusting. If iron is exposed to oxygen at high temperature rapid oxidation or burning will occur with the liberation of more heat. Rapid oxidation or burning does not occur until the kindling temperature of the material is reached. In the case of a liquid this term is called the *flash point*. Oxidation is very important in welding operations since oxygen of the air is usually present as well as heat.

Another chemical definition is reduction, which is the process by which oxygen is taken from another element. The substance used to take the oxygen from the element is called a *reducing agent*. A reducing agent is an element which adds electrons to another element. Hydrogen is one of the most active reducing agents; however, in the case of the iron and oxygen reaction mentioned above, the iron is the reducing agent. Whenever there is an oxidation reaction there is also a reduction reaction. A common term in oxyacetylene welding is **reducing atmosphere** or **oxidizing atmosphere**. The flame can be adjusted to provide sufficient oxygen for complete combustion or an excess of acetylene and insufficient oxygen resulting in incomplete combustion. Acetylene is high in hydrogen and carbon. The oxidizing flame would contribute excess oxygen; the reducing flame would contribute hydrogen and carbon.

The last two definitions are common in chemistry but less common in welding. The words are *acidic* and *basic* and refer to acid or base substances. A measure of basicity or acidity is by means of the pH scale. A pH of 7 is considered the neutral point. Pure water has a pH of 7 since it has the same number of hydrogen ions ($H+$) as hydroxide ions ($OH-$). Acids or acidic substances have an excess of hydrogen ions and have a pH value of less than 7. Bases or basic substances have an excess of hydroxide ions and have a pH value of more than 7. The terms are used in connection with nonmetallic slags used in welding and also used in steelmaking. These slags are related to the coatings of electrodes and have acidic or basic characteristics when heated to steel melting temperatures. Certain types of electrodes are called basic type because their coatings produce basic slags which react with impurities in the weld metal. Basic-type coatings are the low-hydrogen sodium- or potassium-containing types which produce basic slags; the basic slags remove appreciable amounts of undesirable phosphorus and sulfur from the molten weld metal. The celleousic-type electrodes are sometimes called the acidic type since an excess amount of hydrogen is present in the arc atmosphere and in the slag.

QUESTIONS

2-1. What is a weld?

2-2. What are the five basic joints?

2-3. What is the most popular weld type?

2-4. There are approximately how many welding processes?

2-5. How many arc welding processes are there?

2-6. How many welding positions are there?

2-7. Define the word *coalescence*. How does it apply to welding?

2-8. What is the difference between GTAW and GMAW?

2-9. Can all the arc welding processes be used in "all positions"?

2-10. Explain the difference between the welder and the welding operator.

2-11. Name the four activities performed when making a manual arc weld.

2-12. Name the four methods of applying an arc weld.

2-13. Why is a written welding procedure required?

2-14. What method of application requires the highest level of manipulative skill?

2-15. What method of application requires the least manipulative skill?

2-16. What is the polarity of the electrode for reverse polarity welding?

2-17. Where does the deposited metal come from in a nonconsumable electrode welding arc?

2-18. Name the various branches of physics that relate to welding.

2-19. Pure metals and pure gases are elements or compounds?

2-20. What is the difference between a reducing atmosphere and an ordinary atmosphere?

REFERENCE

1. "Standard Welding Terms and Definitions," AWS A3.0, American Welding Society, Miami, Fla.

3

Safety and Health of Welders

OUTLINE

3-1 PERSONNEL PROTECTION AND SAFETY RULES

The safety and health of industrial and construction workers is extremely important. All workers engaged in production and construction are continually exposed to potential hazards. There are a number of safety and health problems associated with welding. When correct precautionary measures are followed, welding is a safe occupation. Health officials state that welding, as an occupation, is no more hazardous or injurious to the health than other metalworking occupations.[1]

Governments have become increasingly active concerning the safety and health of workers and have enacted laws prescribing safety regulations and the publication of safety warnings to ensure the safety of workers. In the United States, the provisions of the Occupational Safety and Health Act (OSHA)[2] becomes the law of the land. It makes many national consensus standards enforceable by law. The most important is the American National Standard "Safety in Welding and Cutting."[3] This standard states that welding and cutting operations pose potential hazards from fumes, gases, electric shock, heat radiation, and sometimes noise. All personnel must be warned against these hazards where applicable by the use of adequate precautionary labeling. The precautionary

WARNING: PROTECT yourself and others. Read and understand this label.

FUMES AND GASES can be dangerous to your health. ARC RAYS can injure eyes and burn. ELECTRIC SHOCK can KILL.

- Read and understand the manufacturer's instructions and your employer's safety practices.
- Keep your head out of the fumes.
- Use enough ventilation, exhaust at the arc, or both, to keep fumes and gases from your breathing zone and the general area.
- Wear correct eye, ear, and body protection.
- Do not touch live electrical parts.
- See American National Standard Z49.1 "Safety in Welding and Cutting" published by the American Welding Society, 550 N.W. LeJeune Rd., Miami, Florida 33126; OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.

DO NOT REMOVE THIS LABEL

FIGURE 3-1 Warning label for arc processes and equipment.

label for arc welding processes and equipment, which is required, is shown in Figure 3-1. There are other more common hazards which apply to all metalworking occupations. These are accidents resulting from falling, from being hit by moving objects, from working around moving machinery, from exposure to hot metal, and so on. Normal precautions are required with regard to these hazards as well.

The hazards that are more or less peculiar to welding are:

- ☐ Electrical shock
- ☐ Arc radiation
- ☐ Air contamination
- ☐ Fire and explosion
- ☐ Compressed gases
- ☐ Welding cleaning
- ☐ Other hazards related to specific processes or occupations

Welders work under a variety of conditions: outdoors, indoors in open areas, in confined spaces, high above the ground, and even under water. They utilize a large number of welding and cutting processes; however, most of these have in common the exposure to fumes, gases, radiation, and heat. Occupational health depends on the conditions and exposures received in the welding environment. Welders are exposed to a number of factors simultaneously. The welding and allied industries have ongoing research programs to study these potential problems. The use of specific welding processes or welding on particular metals does present potential health risks, which will be covered later. Additional information is available in the American Welding Society publication entitled "Effects of Welding on Health" published in 1979, and later parts.[4]

Welding Workplace Safety

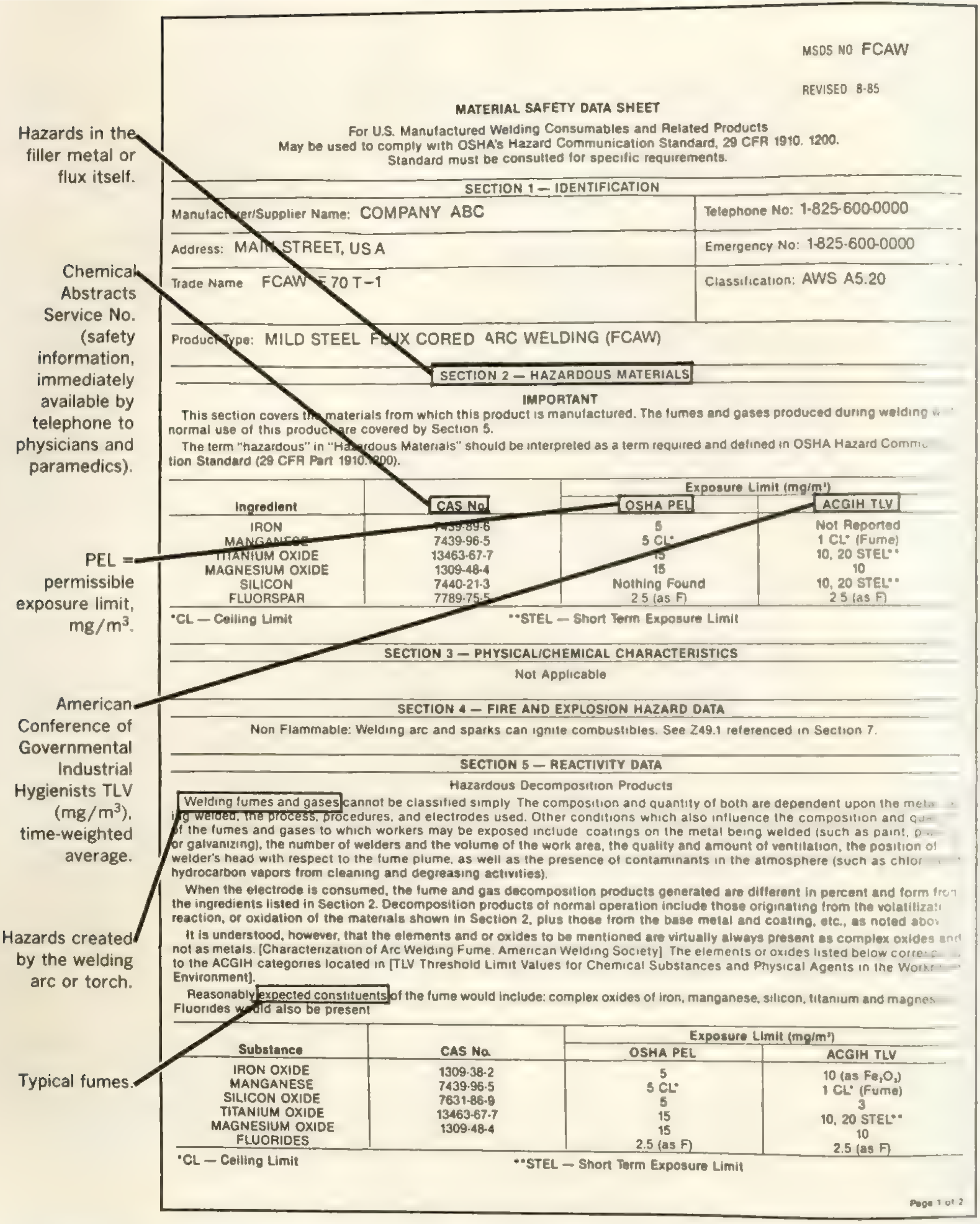
The welding shop management and supervisors are responsible to provide training for the workers in the safe conduct of their day-to-day activities. Employees must be informed and trained so that they are able to detect when hazards are present and protect themselves from them.

The welders and other employees have an obligation to learn and use safe practices and to obey safety rules and regulations. They are responsible for the proper use of equipment and materials. They have an obligation to learn safe practices and to obey safety rules and regulations, and are expected to work in a safe manner. It is the responsibility of supervisors to enforce safety rules and regulations.

Combustible materials must not be allowed to collect in or near the welding workplace. Good housekeeping practices should always be employed in the welding shop. Adequate safety devices should be provided, such as proper fire extinguishers, lifesaving and support equipment, first-aid kits, and so on, plus the training of personnel to utilize this equipment properly. Only approved equipment should be used, and it must be properly installed and maintained in good working order.

Material Safety Data Sheets

OSHA requires that employers must have a comprehensive hazard communication program to inform employees about hazardous substances that might be used in the workplace. The employer must maintain continuous training concerning such materials, and safety in general. Provisions to safeguard employees are the use of Material Safety Data Sheets as prescribed by the Hazard Communication Standard of the U.S. Department of Labor.[5] Information must be provided for all sub-



MSDS NO FCAW

REVISED 8-85

MATERIAL SAFETY DATA SHEET

For U.S. Manufactured Welding Consumables and Related Products
May be used to comply with OSHA's Hazard Communication Standard, 29 CFR 1910. 1200.
Standard must be consulted for specific requirements.

SECTION 1 — IDENTIFICATION

Manufacturer/Supplier Name: COMPANY ABC	Telephone No: 1-825-600-0000
Address: MAIN STREET, USA	Emergency No: 1-825-600-0000
Trade Name FCAW E 70 T-1	Classification: AWS A5.20

Product Type: MILD STEEL FLUX CORED ARC WELDING (FCAW)

SECTION 2 — HAZARDOUS MATERIALS

IMPORTANT

This section covers the materials from which this product is manufactured. The fumes and gases produced during welding w... normal use of this product are covered by Section 5.

The term "hazardous" in "Hazardous Materials" should be interpreted as a term required and defined in OSHA Hazard Comm... tion Standard (29 CFR Part 1910.1200).

Ingredient	CAS No.	Exposure Limit (mg/m^3) OSHA PEL	ACGIH TLV
IRON	7439-89-6	5	Not Reported
MANGANESE	7439-96-5	5 CL*	1 CL* (Fume)
TITANIUM OXIDE	13463-67-7	15	10, 20 STEL**
MAGNESIUM OXIDE	1309-48-4	15	10
SILICON	7440-21-3	Nothing Found	10, 20 STEL**
FLUORSPAR	7789-75-5	2.5 (as F)	2.5 (as F)

*CL — Ceiling Limit **STEL — Short Term Exposure Limit

SECTION 3 — PHYSICAL/CHEMICAL CHARACTERISTICS

Not Applicable

SECTION 4 — FIRE AND EXPLOSION HAZARD DATA

Non Flammable: Welding arc and sparks can ignite combustibles. See Z49.1 referenced in Section 7.

SECTION 5 — REACTIVITY DATA

Hazardous Decomposition Products

Welding fumes and gases cannot be classified simply. The composition and quantity of both are dependent upon the meta... ing welded, the process, procedures, and electrodes used. Other conditions which also influence the composition and qu... of the fumes and gases to which workers may be exposed include coatings on the metal being welded (such as paint, p... or galvanizing), the number of welders and the volume of the work area, the quality and amount of ventilation, the position of welder's head with respect to the fume plume, as well as the presence of contaminants in the atmosphere (such as chlor... hydrocarbon vapors from cleaning and degreasing activities).

When the electrode is consumed, the fume and gas decomposition products generated are different in percent and form fro... the ingredients listed in Section 2. Decomposition products of normal operation include those originating from the volatilizati... reaction, or oxidation of the materials shown in Section 2, plus those from the base metal and coating, etc., as noted abo...

It is understood, however, that the elements and or oxides to be mentioned are virtually always present as complex oxides and not as metals. [Characterization of Arc Welding Fume. American Welding Society] The elements or oxides listed below corre... to the ACGIH categories located in [TLV Threshold Limit Values for Chemical Substances and Physical Agents in the Work... Environment].

Reasonably expected constituents of the fume would include: complex oxides of iron, manganese, silicon, titanium and magnes... Fluorides would also be present.

Substance	CAS No.	Exposure Limit (mg/m^3) OSHA PEL	ACGIH TLV
IRON OXIDE	1309-38-2	5	10 (as Fe_2O_3)
MANGANESE	7439-96-5	5 CL*	1 CL* (Fume)
SILICON OXIDE	7631-86-9	5	3
TITANIUM OXIDE	13463-67-7	15	10, 20 STEL**
MAGNESIUM OXIDE	1309-48-4	15	10
FLUORIDES		2.5 (as F)	2.5 (as F)

*CL — Ceiling Limit **STEL — Short Term Exposure Limit

Page 1 of 2

FIGURE 3-2 Page 1 of material safety data sheet of flux-cored electrode. (From Ref. 7.)

stances taken into the workplace, except foods, drugs, cosmetics, or tobacco products used for personal consumption. Over 600 substances are covered, including welding consumables or filler metals. The use of these data sheets in all manufacturing workplaces has been mandated since 1985. Employees must be taught how to read and interpret information on labels and material data sheets.

Each material data sheet for welding products includes information about every hazardous component comprising of 1% or more of the contents, and for every potential carcinogen (cancer inciting or producing) com-

Gases.

Gaseous reaction products may include carbon monoxide and carbon dioxide. Ozone and nitrogen oxides may be formed by the radiation from the arc.

How to sample actual fumes.

One recommended way to determine the composition and quantity of fumes and gases to which workers are exposed is to take an air sample inside the welder's helmet if worn or in the worker's breathing zone (See ANSI/AWS F1.1, available from the "American Welding Society," P. O. Box 351040, Miami, FL 33135. Also, from AWS is F1.3 "Evaluating Contaminants in the Welding Environment — A Sampling Strategy Guide," which gives additional advice on sampling). At a minimum, materials listed in this section should be analyzed.

SECTION 6 — HEALTH HAZARD DATA

Threshold Limit Value:

The ACGIH recommended general limit for Welding Fume NOC (Not Otherwise Classified) is 5 mg/m³. ACGIH-1985 or latest date) preface states "The TLV-TWA should be used as guides in the control of health hazards and should not be used as fine lines between safe and dangerous concentrations." See Section 5 for specific fume constituents which may modify this TLV.

Effects of Overexposure

Note effects of overexposure.

Electric arc welding may create one or more of the following health hazards:

FUMES AND GASES can be dangerous to your health.

SHORT - TERM (ACUTE) OVEREXPOSURE to welding fumes may result in discomfort such as dizziness, nausea, or dryness or irritation of nose, throat or eyes.

LONG-TERM (CHRONIC) OVEREXPOSURE may lead to siderosis (iron deposits in lungs) and is believed by some investigators to affect pulmonary functions.

ARC RAYS can injure eyes and burn skin.

ELECTRIC SHOCK can kill.

See Section 7.

Apply first aid.

Emergency and First Aid Procedures

Call for medical aid. Employ first aid techniques recommended by the American Red Cross.

Eyes & Skin: If irritation or flash burns develop after exposure, consult a physician.

Beware! (Carcinogenic means it may produce cancer.)

Carcinogenicity

These products do not contain ingredients that are defined as carcinogenic per 29CFR 1910.1200 - Hazard Communication Standard.

SECTION 7 — PRECAUTIONS FOR SAFE HANDLING AND USE/APPLICABLE CONTROL MEASURES

Read and understand the manufacturer's instructions and the precautionary label on the product. (See American National Standard Z49.1, Safety in Welding and Cutting published by the American Welding Society, P. O. Box 351040, Miami, FL 33135 and OSHA Publication 2206 (29CFR1910), U.S. Government Printing Office, Washington, D.C. 20402. For more detail on many of the following:)

Ventilate weld area.

VENTILATION: Use enough ventilation, local exhaust at the arc, or both, to keep the fumes and gases below TLV's in the worker's breathing zone and the general area. Train the welder to keep his head out of the fumes.

Use respirator when necessary.

RESPIRATORY PROTECTION: Use NIOSH approved or equivalent fume respirator or air supplied respirator when welding in confined space or where local exhaust or ventilation does not keep exposure below TLV.

Wear helmet, filter lens.

EYE PROTECTION: Wear helmet or use face shield with filter lens. As a rule of thumb begin with Shade Number 14. Adjust if needed by selecting the next lighter and/or darker shade number. Provide protective screens and flash goggles, if necessary, to shield others.

Protect from radiation, sparks, electric shock, hot metal, sharp edges, pinch points, falls.

PROTECTIVE CLOTHING: Wear hand, head, and body protection which help to prevent injury from radiation, sparks, and electrical shock. See ANSI Z49.1. At a minimum this includes welder's gloves and a protective face shield, and may include arm protectors, aprons, hats, shoulder protection, as well as dark substantial clothing. Train the welder not to touch live electrical parts and to insulate himself from work and ground.

PROCEDURE FOR CLEANUP OF SPILLS OR LEAKS: Not applicable

WASTE DISPOSAL: Prevent waste from contaminating surrounding environment. Discard any product, residue, disposable container or liner in an environmentally acceptable manner, in full compliance with federal, state and local regulations.

Never exceed permissable exposure limits.

SPECIAL PRECAUTIONS: IMPORTANT: Maintain exposure below the PEL/TLV. Use industrial hygiene monitoring to ensure that your use of this material does not create exposures which exceed PEL/TLV. Always use exhaust ventilation. Refer to the following sources for important additional information.

ANSI Z49.1 The American Welding Society, P. O. Box 351040, Miami, FL 33135 — OSHA (29CFR1910) U.S. Dept. of Labor, Washington, D.C. 20210.

Protect yourself. The manufacturer disclaims any responsibility.

Manufacturer believes these data to be accurate and to reflect qualified expert opinion regarding current research. However, Manufacturer cannot make any express or implied warranty as to this information.

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FIGURE 3-3 Page 2 of material safety data sheet of flux-cored electrode. (From Ref. 7.)

prising 0.1% or more. The components are included in the listing by the American Conference of Governmental Industrial Hygienists, with threshold limit values.[6]

Material safety data sheets should be obtained from suppliers of welding electrodes, fluxes, and so on. They should be kept on file in the personnel or welding departments. The training program must cover not only welders but others working in the welding area, such as service personnel, maintenance personnel, regular visitors to the welding shop, and others. A typical material safety data sheet[7] for a flux-cored arc welding electrode is shown by Figures 3-2 and 3-3. Particular points of interest are high-

lighted to provide more data for intelligent interpretation of this information. The OSHA Hazard Communications Standard includes Appendix A, which requires employers to report any adverse health effects for which there is scientific evidence. Appendix B provides guidance in recognizing hazards. The Hazardous Communication Program and Welding Safety Training Programs must be ongoing.

Heat Exposure

Welders are sometimes required to weld on, or even inside, preheated weldments. The preheat temperatures required for welding special materials can be quite high and the welder must be protected from coming into contact with the hot metal. Workers should be supplied with sufficient cool air to avoid breathing excessively hot air. Special precautions must be taken and special procedures must be adopted to protect the welder from the heat. Protective clothing should be worn, which helps insulate the welder from excessive heat. Consultation with safety experts and just plain common sense are required in these situations.

Protective Clothing

Welders should wear work or shop clothes without openings or gaps to prevent the arc rays from contacting the skin. If the arc rays contact the skin for a period of time, painful "sunburns" or "arc burns" will result. People working close to arc welding should also wear protective clothing.

For light-duty welding, normally 200 A or lower, the level of protection can be reduced. Figure 3-4 shows a welder dressed for light-duty work. Woolen clothing is much more satisfactory than cotton since it will not disintegrate from arc radiation or catch on fire as quickly. Cloth gloves can be used for light-duty work. For heavy-duty work, more thorough protective clothing is required. Figure 3-5 shows a welder dressed for heavy-duty welding work, wearing leather gauntlet gloves, a leather jacket, leather apron, and spats, which also pro-

FIGURE 3-4 Welder dressed for light-duty welding.

FIGURE 3-5 Welder dressed for heavy-duty welding.

tect against sparks and molten metal. When welding in the vertical and overhead position, this type of clothing is required. In all cases a headcap should be used. Flame-retardant clothing should be worn. Clothing should always be kept dry, and this applies to gloves as well. High-top shoes with safety toes are recommended. The leather clothes should be of the chrome-tanned type. Leather gloves should not be used to pick up hot items since this will cause the leather to become stiff and crack. Protective clothing must be kept in good repair. Hard hats should be checked occasionally. Gloves should be clean and not oily. Welding helmets should be checked for cracks, and filter glasses should be replaced if damaged.

Signs should be posted in the welding department pointing out precautions that must be taken by employees and visitors in the welding shop. These signs should be in agreement with ANSI Standard "Specifications for Accident Prevention Signs."[8] The welding department should also be posted warning people with heart pacemakers that they should not enter or should take special precautions.

Safety Rules

The following sets of 20 rules, "Safety Precautions for Arc Welding" and "Safety Precautions for Oxyacetylene Welding and Cutting," should be posted in the welding shop.

Safety Precautions for Arc Welding

1. Make sure that your arc welding equipment is installed properly and grounded and is in good working condition.
2. Always wear protective clothing suitable for the welding to be done.
3. Always wear proper eye protection when welding, spraying, cutting, or grinding.
4. Avoid breathing the air in the fume plume directly above the arc.
5. Keep your work area clean and free of hazards. Make sure that no flammable, volatile, or explosive materials are in or near the work area.
6. Handle all compressed gas cylinders with extreme care. Keep caps on when not in use.
7. Make sure that compressed gas cylinders are secured to the wall or to other structural supports.
8. When compressed gas cylinders are empty, close the valve and mark the cylinder "empty."
9. Do not weld in a confined space without special precautions.
10. Do not weld on containers that have held combustibles without taking special precaution.
11. Do not weld on sealed containers or compartments without providing vents and taking special precautions.
12. Use mechanical exhaust at the point of welding when welding lead, cadmium, chromium, manganese, brass, bronze, zinc, or galvanized steel, and when welding in a confined space.
13. When it is necessary to weld in a damp or wet area, wear rubber boots and stand on a dry insulated platform.
14. Do not use cables with frayed, cracked, or bare spots in the insulation.
15. When the electrode holder is not in use, hang it on the brackets provided. Never let it touch a compressed gas cylinder.
16. Dispose of electrode stubs in proper container since stubs on the floor are a safety hazard.
17. Shield others from the light rays produced by your welding arc.
18. Do not weld near degreasing operations.
19. When working above ground make sure that the scaffold, ladder, or work surface is solid.
20. When welding in high places, use a safety belt or lifeline.

Safety Precautions for Oxyacetylene Welding and Cutting

1. Make sure that all gas apparatus shows UL or FM approval, is installed properly, and is in good working condition. Make sure that all connections are tight before lighting the torch. Do not use a flame to inspect for tight joints. Use soap solution to detect leaks.
2. Always wear protective clothing suitable for welding or flame cutting.
3. Keep work area clean and free of hazardous materials. When flame cutting, sparks can travel 30 to 40 ft (10 to 15 m). Do not allow flame cut sparks to hit hoses, regulators, or cylinders.
4. Handle all compressed gas cylinders with extreme care. Keep cylinder caps on when not in use.
5. Make sure that all compressed gas cylinders are secured to the wall or to other structural supports. Keep acetylene cylinders in the vertical position.
6. Store compressed gas cylinders in a safe place with good ventilation. Acetylene cylinders and oxygen cylinders should be kept apart.
7. When compressed gas cylinders or fuel gas cylinders are empty, close the valve and mark the cylinder "empty."
8. Use oxygen and acetylene or other fuel gases with the appropriate torches and only for the purpose intended.

9. Avoid breathing the air in the fume plume directly above the flame.
10. Never use acetylene at a pressure in excess of 15 psi (103.4 kPa). Higher pressure can cause an explosion.
11. Never use oil, grease, or any material on any apparatus or threaded fittings in the oxyacetylene or oxyfuel system. Oil and grease in contact with oxygen may cause spontaneous combustion.
12. Do not weld or flame cut in a confined space without taking special precautions.
13. When assembling apparatus, crack the gas cylinder valve before attaching regulators ("cracking" means opening the valve on a cylinder slightly, then closing). This blows out any accumulated foreign material. Make sure that all threaded fittings are clean and tight.
14. Always use this correct sequence and technique for lighting a torch.
    (a) Open acetylene cylinder valve.
    (b) Open acetylene torch valve ¼ turn.
    (c) Screw in acetylene regulator adjusting valve handle to working pressure.
    (d) Turn off acetylene torch valve (you will have purged the acetylene line).
    (e) Slowly open oxygen cylinder valve all the way.
    (f) Open oxygen torch valve ¼ turn.
    (g) Screw in oxygen regulator screw to working pressure.
    (h) Turn off oxygen torch valve (you will have purged the oxygen line).
    (i) Open acetylene torch valve ¼ turn and light with lighter (use friction-type lighter or special provided lighting device only).
    (j) Open oxygen torch valve ¼ turn.
    (k) Adjust to neutral flame.
15. Always use this correct sequence and technique of shutting off a torch.
    (a) Close acetylene torch valve first, then close oxygen torch valve.
    (b) Close cylinder valves—the acetylene valve first, then the oxygen valve.
    (c) Open torch acetylene and oxygen valves (to release pressure in the regulator and hose).
    (d) Back off regulator adjusting valve handle until no spring tension is felt.
    (e) Close torch valves.

    Note: Different torch manufacturers recommend different shutdown procedures for the torch acetylene and oxygen valves. Follow the procedure recommended for the torch in use. If the oxygen valve is closed first, the yellow sooty acetylene flame enlarges appreciably and could burn the welder. The carbon soot will deposit in the area. If the acetylene valve is closed first, there will be a loud "bang," which may distract nearby welders. In either case the other valve should be closed quickly.
16. Use mechanical exhaust when welding or cutting lead, cadmium, chromium, manganese, brass, bronze, zinc, or galvanized steel.
17. If you must weld or flame cut with combustible or volatile materials present, take extra precautions, make out hot work permit, provide for a lookout, and so on.
18. Do not weld or flame cut on containers that have held combustibles without taking special precautions.
19. Do not weld or flame cut into sealed container or compartment without providing vents and taking special precautions.
20. Do not weld or cut in a confined space without taking special precautions.

The Safety in Welding and Cutting standard also provides a warning label for oxyfuel gas processes (Figure 3-6).

WARNING: PROTECT yourself and others. Read and understand this label.

FUMES AND GASES can be dangerous to your health. HEAT RAYS (INFRARED RADIATION from flame or hot metal) can injure eyes.

- **Read and understand the manufacturer's instructions and your employer's safety practices.**
- **Keep your head out of the fumes.**
- **Use enough ventilation, exhaust at the flame, or both, to keep fumes and gases from your breathing zone, and the general area.**
- **Wear correct eye, ear, and body protection.**
- **See American National Standard Z49.1, "Safety in Welding and Cutting," published by the American Welding Society, 550 N.W. LeJeune Rd., Miami, Florida 33126: OSHA Safety and Health Standards, 29 CFR 1910, available from U.S. Government Printing Office, Washington, DC 20402.**

DO NOT REMOVE THIS LABEL

FIGURE 3-6 Warning label for oxyfuel gas processes. (From Ref. 3.)

If the hazards mentioned in this chapter are properly and adequately handled, the welder is as safe as any other industrial worker. There must be continual vigilance over safety conditions and safety hazards. Safety meetings should be held regularly. The safety rules should be reissued annually and they must be completely understood and enforced.

3-2 ELECTRICAL SHOCK HAZARD

The shock hazard is associated with all electrical equipment. This includes extension lights, electric hand tools, and all types of electrically powered machinery. Ordinary household voltage (115 V) is higher than the output voltage of a conventional arc welding machine.

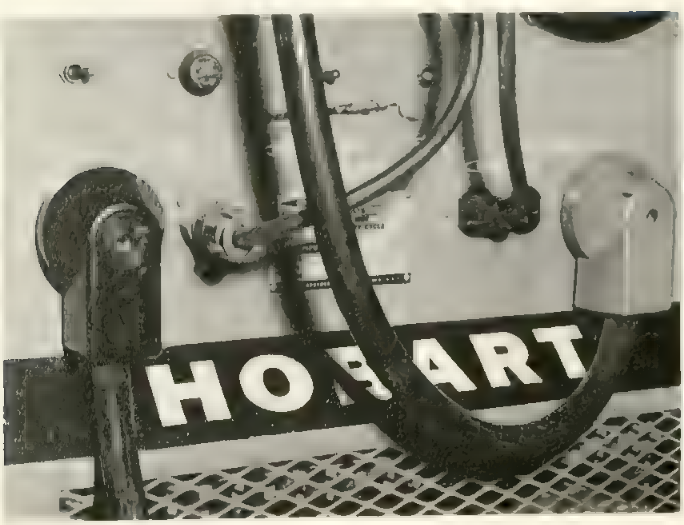
Use only welding machines that meet recognized national standards. Most industrial welding machines meet the National Electrical Manufacturers Association (NEMA) standards for electric welding apparatus.[9] This is mentioned in the manufacturer's literature and is shown on the nameplate of the welding machine. In Canada approval by the Canadian Standards Association is required for certain types of welding machines and this is also indicated on the nameplate.[10] In certain parts of the United States, and for certain applications, the Underwriters' Laboratories approval is required for transformer-type welding power sources.[11] The NEMA specification provides classes of welding machines, duty cycle requirements, and no-load voltage maximum requirements. To comply with the OSHA requirements, manufacturers have made changes to improve the safety of the machines. This includes the covering of the output terminals with insulating devices (Figure 3-7). They have also made the ventilating holes smaller so that the welder cannot come in contact with the high voltage inside the case. They have changed the cases of the welding machines so that "tools" are required to open the case where high voltage is exposed.

Only insulated-type welding electrode holders should be used for shielded metal arc welding. Semiautomatic welding guns for continuous wire processes should utilize low-voltage control switches so that high voltage is not brought into the hands of the welder. In fully automatic equipment, higher voltages are permitted but are inaccessible to the operator during normal operation.

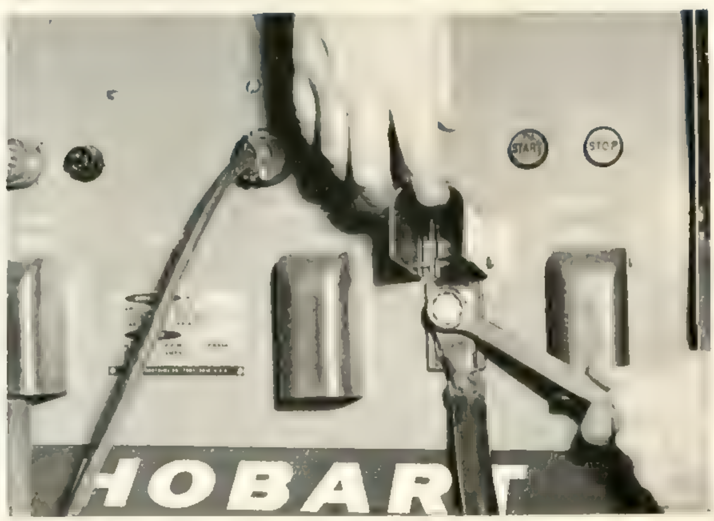
Installation of Welding Machines

All electric arc welding machines must be installed in accordance with the *National Electrical Code*®[12] and all local codes. Installation instructions are included in the manufacturer's manual that accompanies the welding machine. The manual also gives the size of the power cable that should be used to connect the machine to the main line. Motor generator welding machines feature complete separation of the primary power and the welding circuit since the generator is mechanically connected to the electric motor. However, the metal frames and cases of motor generators must be grounded since the high voltage from the main lines does come into the case. In transformer and rectifier machines, the primary and secondary transformer windings are electrically isolated from each other by insulation. This insulation may become defective in time if proper maintenance practices are not observed. The metal frame and cases of transformers and transformer rectifier machines must be grounded to earth. The work terminal of the welding machine should not be grounded to earth. Disconnect

FIGURE 3-7 Insulating devices on terminals of a welding machine.



(a)



(b)

switches should be employed with all power sources so that they can be disconnected from the main lines for maintenance.

It is extremely important when paralleling transformer welding machines that the phases of a three-phase power line be accurately identified. This will ensure that the machines will be on the same phase and "in phase" with one another. It is relatively easy to check this by connecting the work leads together and measuring the voltage between the electrode holders of the two machines. This voltage should be practically zero. If it is double the normal open-circuit voltage, it means that either the primary or secondary connections are reversed. If the voltage is approximately 1½ times the normal open-circuit voltage, it means that the machines are connected to different phases of the three-phase power line. Corrections must be made before welding begins.

When large weldments, such as ships, buildings, or structural parts, are involved, it is normal to have the work terminal of many welding machines connected to it. It is extremely important that the machines be connected to the proper phase and have the same polarity. This can be checked by measuring the voltage between the electrode holders of the different machines mentioned above. The situation can also occur with respect to direct-current power sources when they are connected to a common weldment. If one machine is connected for straight polarity and one for reverse polarity, the voltage between the electrode holders will be double the normal open-circuit voltage. Precautions should be taken to see that all machines are of the same polarity when connected to a common weldment. Simultaneous welding with ac and dc welding machines must not be permitted on the same weldment.

The welding electrode holders must be connected to machines with flexible cables designed for welding application. There must be no splices in the electrode cable within 10 ft (3 m) of the electrode holder. Splices, if used in work or electrode leads, must be insulated.

Finally, it is important to locate welding machines where they have adequate ventilation and that ventilating ports be so located that they cannot be obstructed.

Use of Welding Machines

Electrode leads and work leads should not be coiled around the welding machines, nor should they ever be coiled around the welder. Electrode holders should not be hung where they can accidentally come in contact with the other side of the circuit. Electrodes should be removed from holders whenever they are not in use. It is absolutely essential that power cables or primary power coming to a welding machine not be intermixed or come in contact in any way with the welding cables. The welding machine must be kept dry, and if it should become wet, it should be dried properly by competent electrical maintenance personnel. In addition, the work area must be kept dry. Welders should never work in water or damp areas since this reduces the resistance to the welder and increases potential electrical hazard.

Welders should not make repairs on welding machines or associated equipment. Welders should be instructed not to use tools to open cases of welding machines. They should be instructed not to perform maintenance on electrode holders, welding cables, welding guns, wire feeders, and so on. Instead, they should be advised to notify their supervisors of maintenance problems or potential hazards so that qualified maintenance personnel can make needed repairs.

Maintenance of Welding Machines

Welding machines and auxiliary equipment must be inspected periodically and maintained by competent electricians. During maintenance the equipment must be disconnected from main power lines so that there is no possibility of anyone coming in contact with the high input voltage. Maintenance records should be kept on welding power supplies to comply with OSHA regulations. Supervisors and maintenance personnel should make routine inspection of welding cables and electrode holders, guns, and work clamps. Welders should report defective equipment or problems to their supervisors. Electrode holders with worn or missing insulators, and worn and frayed cables, should be repaired or replaced. Wire feeding semiautomatic equipment and specialty equipment, designed for gas tungsten arc welding, normally utilize power contractors. This means that the electrode wire or torch is electrically "cold" except while welding. The trigger on the welding gun or foot switch or programmer closes the contractors that energize the welding circuit. Arc voltage is normally nonhazardous.

3-3 ARC RADIATION HAZARD

The electric arc is a very powerful source of light: visible, ultraviolet, and infrared. It is necessary that welders and others close to the welding arc wear suitable protection from the arc radiation. The brightness and exact spectrum of a welding arc depend on the welding process, the metals in the arc, the arc atmosphere, the length of the arc, and the welding current. The higher the current and arc voltage, the more intense the light from the arc. Like all radiation, arc light radiation decreases with the square of the distance. Those processes that produce smoke surrounding the arc have a less bright arc since the smoke acts as a filter. The spectrum of the welding arc is similar to that of the sun. Exposure of the skin and eyes to the arc is the same as exposure to the sun. If they are using a thoriated tungsten electrode for the gas

tungsten arc welding process, welders sometimes suspect that there is x-radiation in the arc. Radiation is minute, and exhaustive tests have proven that such worries are needless.[13]

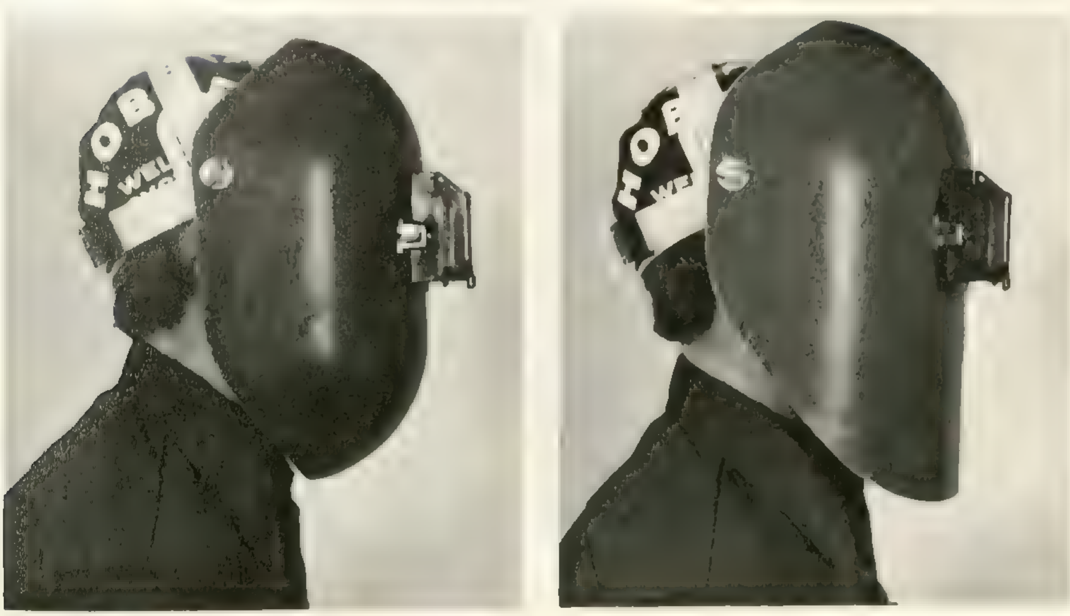
Heat is radiated from the arc in the form of infrared radiation. The infrared radiation is harmless provided that the proper eye protection and clothing are worn. To minimize light radiation, screens should be placed around the welding area so that people working nearby are shielded from the arc. Welders should attempt to screen all people from their arc. Screens and surrounding areas, especially welding booths, should be painted with flat finish paints that absorb ultraviolet radiation yet do not create high contrast between the bright and dark areas. The flat paint finish should have a low reflectivity to ultraviolet radiation. Light pastel colors of a zinc oxide or a titanium dioxide paint are recommended. Black paint or glossy finish paint should not be used.

Eye Protection

Welders must use protective welding helmets with special filter plates or filter glasses. The welding helmets should be in good repair since openings or cracks can allow arc light to get through and create discomfort. The curved front welding helmets are preferred over straight front because they reduce the amount of welding fumes that come to the welder's breathing zone. Figure 3-8 shows both types of welding helmets. Fiberglass is recommended for its light weight. Welding helmets can be attached to safety hard hats for industrial and construction work. Welding helmets have lens holders for inserting the cover glass and filter glass or plate. The standard-size filter plate is 2 × 4¼ in. (50 × 108 mm). In some helmets, the lens holders will open or flip upward. Helmets that accommodate larger-size filter lenses are also available and are used for special work. The larger filter glasses are 4½ × 5¼ in. (115 × 133 mm) and are more expensive. The filter glasses or plates come in various optical densities to filter out a portion of the arc rays. The shade of the filter glass used is based on the welding process, the type of base metal, and the welding current. Figure 3-9 shows the proper filter shades according to the American Standard "Practice for Occupational and Educational Eye and Face Protection." A cover plate should be placed on the outside of the filter glass to protect it from weld spatter. Plastic or glass plates are used. Some welders also use magnifier lenses behind the filter plate to provide clearer vision. The filter glass must be tempered so that it will not break if hit by flying objects. Filter glasses must be marked showing the manufacturer, the shade number, and the letter H, indicating that it has been treated for impact resistance.

Several new types of filter lens for welding helmets have been introduced recently. One type of filter glass utilizes a thin layer of liquid crystals sandwiched between two pieces of clear glass. The liquid crystals employed have special properties, so that when an electrical signal is placed across them, they will change their ability to transmit light. When electrically changed the liquid crystals produce a screen with the same approximate density as the welding filter glass. A photosensor on the helmet is triggered by the light from the arc. Within a hundredth of a second this signal is transmitted through the liquid crystals, which change the density of the filter glass. Another type of filter becomes darker when ex-

FIGURE 3-8 Welding helmets, curved and straight front type.



Welding or Cutting Operation	Electrode Size Metal Thickness, or Welding Current	Filter Shade Number
Torch soldering		2
Torch brazing		3 or 4
Oxygen cutting		
Light	Under 1 in., 25 mm	3 or 4
Medium	1 to 6 in., 25 to 150 mm	4 or 5
Heavy	Over 6 in., 150 mm	5 or 6
Gas welding		
Light	Under ⅛ in., 3 mm	4 or 5
Medium	⅛ to ½ in., 3 to 12 mm	5 to 6
Heavy	Over ½ in., 12 mm	6 or 8
Shielded metal arc	Under 5/32 in., 4 mm	10
welding (stick)	5/32 to ¼ in., 4 to 6 mm	12
electrodes	Over ¼ in., 6.4 mm	14
Gas metal arc welding (MIG)		
Nonferrous base metal	All	11
Ferrous base metal	All	12
Gas tungsten arc welding (TIG)	All	12
Atomic hydrogen welding	All	12
Carbon arc welding	All	12
Plasma arc welding	All	12
Carbon arc air gouging		
Light		12
Heavy		14
Plasma arc cutting		
Light	Under 300 A	9
Medium	300 to 400 A	12
Heavy	Over 400 A	14

FIGURE 3-9 Eye protection filter shade selector. (From Ref. 14.)

posed to the bright light of the arc. These filters are becoming more popular since they eliminate the need for opening and closing or repositioning the welding helmet. These new-style filter lenses have not yet been included in the safety standards; however, testing is under way.

Safety glasses should be worn underneath the welding helmet. These are required since the helmet is usually lifted when slag is chipped or welds are ground. Tinted safety glasses with side shields are recommended. People working around welders should also wear tinted safety glasses with side shields. Safety glasses should meet all the requirements of the eye and face protection standard.[14]

Contact Lenses

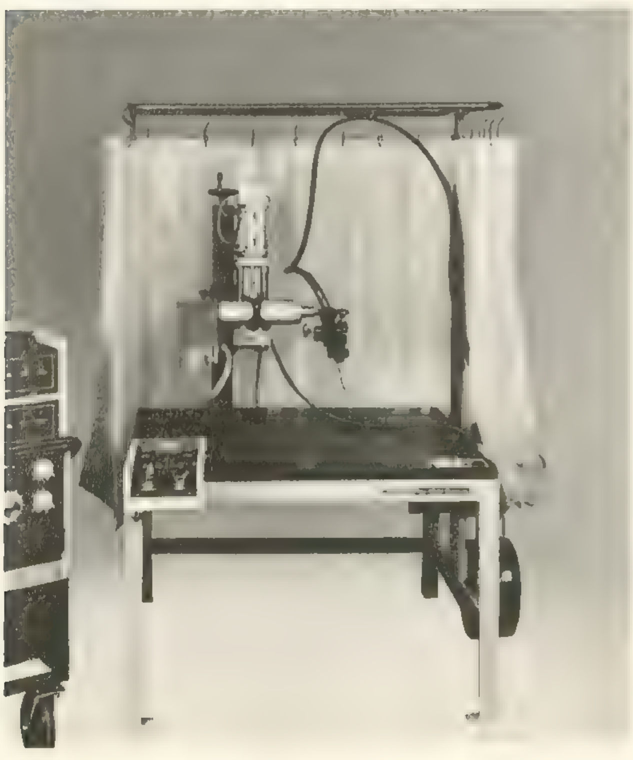
The wearing of contact lenses by welders is the subject of erroneous and recurring rumors. Various authorities, including the National Society to Prevent Blindness, the Contact Lens Association of Ophthalmologists, and others, state that the normal eye protection required by OSHA for welding, brazing, and soldering is the same with or without contacts. The American Optometric Association adopted a policy statement saying that contact lenses may be worn in hazardous environments with appropriate normal safety eye wear. Contact lenses of themselves do not provide eye protection in the industrial sense. As a general rule, if an employee habitually wears contact lenses, he or she should be allowed to wear his or her own lenses in addition to normal safety equipment. It was further noted that the heat from the welding arc or flash is not intense enough to affect the durable plastic from which contact lenses are made. Welders or anyone who may be exposed to a welding flash or arc should wear appropriate safety goggles over their contact lenses. Eye experts unanimously agree that it is impossible for an electric arc to weld contact lenses to the eye. The American Optometric Association says that reports of this hazard are based on rumor and have been thoroughly discredited. Both OSHA and the U.S. Food and Drug Administration stated that the reports of this accident were false and there is no such danger.

On occasion, welders and others will have their eyes exposed to the arc for a short period. This will result in what is known as "arc burn," "arc flash," or "welding flash" and is technically called "photokeratitis." It is very similar to a sunburn of the eye. For a period of approximately 24 hours the welder will have the painful sensation of sand in the eyes. The condition is normally of temporary duration and should not last over 48 hours. The welder who receives an arc flash may not be aware of it at the time. The first indication of an arc burn may occur 6 to 12 hours later in the middle of the night. Temporary relief can be obtained by using eyedrops and eyewashes. If the painful sensation lasts beyond one day, a doctor should be consulted for treatment.

Transparent Welding Curtains

Transparent welding curtains made of polyvinyl chloride plastic film are sometimes used for screening welding operations (Figure 3-10). The material is about 0.012 in. thick (0.3 mm), relatively tough, available in large sheets, and comes in blue, green, gray, and yellow. Tests have been performed by the National Institute of Occupational Safety and Health,[15] and it is concluded that these curtains provide protection in the ultraviolet range. The gray color provides the most protection, with yellow providing the least. They meet requirements of OSHA. The age of curtains may have an effect. The material is flame resistant. In no case can this curtain material be substituted for filter glass in helmets. It is intended to protect nearby workers from arc flash and improve communication with welders. In this application it is an improvement over opaque curtains or shields.

FIGURE 3-10 Automatic welding station using transparent welding curtains.



Other Factors

Welding operations should be isolated from metal-degreasing or solvent-cleaning operations. Chemical-degreasing tanks may use trichloloethylene or other chlorinated hydrocarbons which will decompose to phosgene gas when exposed to arc (ultraviolet) radiation. Phosgene can build up to dangerous concentrations which will be potentially harmful. Fortunately, the odor of phosgene gas is quickly recognized (it smells like new-mown hay), and if it is detected, the area should be evacuated and ventilated. Degreasing operations should be at least 200 ft away from welding operations. If this is not possible, adequate ventilation is required. Care should be taken when welding parts that have been cleaned with these solvents. The surface must be thoroughly dry before welding.

Ultraviolet rays from the arc, particularly the high-intensity gas tungsten arc on aluminum, react with the oxygen in the atmosphere to produce ozone. Ozone is an active form of oxygen which has a sweet smell. It is sometimes evident after a lightning strike or in the generating room of a powerhouse. It is relatively unstable and quickly recombines to oxygen. Exposure to ozone will cause a burning sensation in the throat, coughing or chest pains, or wheezing in the chest during breathing. Ventilation should be used so that ozone concentration will be below the threshold limit values.

Warning signs should be posted in welding departments advising visitors not to look at the arc, since arc flash may injure eyes.

3-4 AIR CONTAMINATION HAZARD

Arc welding and flame cutting do produce air contamination. This is identified as smoke rising above the welding or flame cutting operation. The smoke or plume appears similar to smoke rising from a wood fire or backyard barbecue grill. Normal ventilation practice reduces the hazards of smoke from either welding or an open fire. The welding fumes contain two types of air contamination: particulate matter and gases.

The welding industry, through the American Welding Society, has sponsored research to investigate the welding atmosphere and to recommend precautions to avoid potential hazards. This includes a series of reports entitled "Effects of Welding on Health" mentioned previously, starting in 1979 and continuing. The American Welding Society's study entitled "The Welding

Environment"[16] and several foreign studies indicate that there is no significant health difference between welders and nonwelders when the welding process is carried out with adequate ventilation.

A warning label introduced in 1967 states: "**Caution:** Welding may produce fumes and gases hazardous to health. Avoid breathing these fumes and gases. Use adequate ventilation. See American National Standard Z49.1 Safety in Welding and Cutting published by the American Welding Society."[3]

This label was revised in 1979 to be more encompassing and is shown in Figure 3-1. A similar warning label for oxyfuel gas processes is shown in Figure 3-6. The purpose of these labels is to remind welders and companies employing welders of the potential hazard, so that adequate steps are taken to protect personnel from concentrations that might be harmful. The potential harm from fumes and gases depends on:

- The chemical composition of the particulate matter
- The concentration at the welder's breathing zone
- The length of time of exposure to these fumes and gases

Particulate Matter

Particulate matter is extremely small solids suspended in the air. Smoke is an example of particulate matter. Particulate matter includes common house dust, powders, pollen, smog, fly ash, grinding dust, and so on. These range in size from less than 0.1 micron (μm) to over 100 μm. The smaller-diameter particulates can only be seen with a microscope, while the larger ones can be seen with the human eye. The type of particulate matter relates to the welding process, the type of welding electrode or filler metal, the welding current employed, and the welding location, atmospheric conditions, wind, and so on. It also depends on the composition of the base metal being welded and on any coating on the base metal in the arc area. All welding smoke is not the same and the concentration can vary over a wide range.

Many investigations and tests have been made to determine the composition of fumes generated. This is presented in the AWS publication "The Welding Environment" mentioned previously, and was based on using different welding and allied processes. Many data are presented in the document "Fumes and Gases in the Welding Environment."[17] Research to determine fume generated by arc welding is given by the document "Characterization of Arc Welding Fume."[18] In general, welding with mild steel electrodes on clean steel produces fumes containing a high proportion of iron oxide and small amounts of calcium oxide, titanium oxide, and amorphous silica. The fumes produced when welding with low-hydrogen-type electrodes contain the oxides mentioned above and fluorides. When welding with stainless steel electrodes, the iron oxide is lower but there are now oxides of chromium and nickel as well as fluorides. Electrode manufacturers supply **material safety data sheets** (MSDSs) in each container of filler metals, which show the composition of the coating on electrodes, fluxes, or flux cores. Data sheets may also include the composition of particulate matter produced as these electrodes are consumed in the arc. Due to the high temperature of the arc, the composition of the particulate matter is different from that of the coating.

The flux-cored arc welding process seems to produce the most particulate matter, or smoke. This appears true with the nonexternal gas-shielded electrode wire. However, compared to the amount of weld metal deposited, the particulate matter of both processes is very similar. The gas metal arc welding process produces much less particulate matter and the submerged arc process produces a very small amount of particulate matter, as do the gas tungsten and plasma arc welding processes.

The base material is another source of particulate matter. When melted by an arc, the base metal may volatilize and produce airborne contaminants. Chromium and nickel compounds are found in the fume when stainless steels are arc welded. The American Welding Society has developed a standardized method for measuring and determining the particulate matter produced by different welding processes. This method is outlined by the AWS document "Method for Sampling Airborne Particulates Generated by Welding and Allied Processes."[19] By using this technique, measurements can be made to determine contamination.

Certain metals should not be welded without the use of mechanical exhaust systems because the vaporized metals are potentially hazardous. The common metals that create hazardous airborne contaminations are beryllium, brass, bronze, cadmium, chromium, cobalt, copper, lead, manganese, nickel, vanadium, and zinc. Arc welding should not be done on any of these metals unless mechanical ventilation is employed or unless the welder is protected in some other manner.

Airborne contaminants are produced when welding or flame cutting on coated materials. Base metal coated with any of the metals listed above must be treated with caution and mechanical ventilation must be provided. Other coatings, such as paint, varnish, plastic, and oil, can also generate contamination. The coatings must be removed from the welding area or mechanical ventilation must be provided. A serious problem can be encountered when old steel work is flame cut or welded. Often, older structural steel may be covered with many coats of lead-bearing paint. The heat of the arc or flame will cause the coating to volatilize and produce smoke containing lead. New pipe is often coated with a protective material. This must be removed from the arc area. In either case, adequate ventilation or protection for the welder must be employed.

Gases

Gases are produced or may be involved in many of the welding processes in oxygen flame cutting and allied processes. Gases are produced as products of combustion with the fuel gas processes. Gas is produced when steel is melted in the arc. Gas is produced by some of the constituents of the coating on the shielded metal arc welding electrode or the material contained in the core of a flux-cored electrode wire. These coating and contained materials are designed as a part of the consumable filler metal to produce gases to help shield the arc area from the atmosphere. Packages of filler metals carry a warning label which is the same as Figure 3-1.

Fluxes used for gas welding and brazing, and for submerged arc welding and electroslag welding, will also produce gases when they are heated. Brazing and gas welding fluxes sometimes contain fluoride, and heating or melting produces small amounts of fluorine in the atmosphere. Packages containing these types of fluxes are labeled as shown in Figure 3-11. These products produce potentially harmful gases, and adequate ventilation should be employed.

Carbon dioxide is the most common gas produced by the disintegration of electrode coatings or materials in flux-cored electrode wires. The CO_2 is used to help protect the arc area from the atmosphere. There is a possibility of carbon monoxide gas being produced in the arc. Carbon monoxide, however, readily recombines with available oxygen in the heated atmosphere to produce CO_2 gas. Carbon monoxide is rarely found beyond a short distance away from the arc area.

Ozone is sometimes produced by the ultraviolet light emitted by the arc. Ozone is a form of oxygen with a chemical formula of O_3, and is over 1½ times as dense as oxygen. Ozone is more often produced in the arc welding processes that do not employ fluxes or coatings. Ozone is less of a hazard since it changes back to normal oxygen a short distance from the arc.

The gas-shielded welding processes utilize various gases to shield or protect the arc area from the atmosphere. Inert gases are used for gas tungsten arc welding and for plasma arc welding, but active gases or mixtures of active and inert gases are used for gas metal arc and flux-cored arc welding. Adequate ventilation is required to remove these gases from the welder's breathing zone.

Confined or Enclosed Areas

All welding and flame cutting operations, and associated operations, carried out in confined or restricted spaces must be adequately ventilated to prevent the accumulation of toxic materials, combustible gases, or oxygen deficiency.

An enclosed area, also called a confined space, is a relatively small or restricted space such as a tank, vat, pressure vessel, boiler, compartment, small room, or any enclosure which may have poor ventilation. Enclosed areas, which also include tunnels, pose problems not only for welders but for anyone working inside them. The potential hazards range from deficiency of oxygen, too much oxygen, poisonous gases, flammable or explosive gases, to the accumulation of dense smoke or particulate matter. Welding, flame cutting, or allied processes should never be started without taking special precautions. In addition, apparatus should never be taken into the enclosed area.

WARNING: CONTAINS FLUORIDES. Protect yourself and others. Read and understand this label.

FUMES AND GASES CAN BE DANGEROUS TO YOUR HEALTH. BURNS EYES AND SKIN ON CONTACT. CAN BE FATAL IF SWALLOWED.

- **Read, understand, and follow the manufacturer's instructions and your employer's safety practices.**
- **Keep your head out of the fume.**
- **Use enough ventilation, exhaust at the work, or both to keep fumes and gases from your breathing zone and the general area.**
- **Avoid contact of flux with eyes and skin.**
- **Do not take internally.**
- **Keep out of reach of children.**
- **See American National Standard Z49.1, "Safety in Welding and Cutting," available from the American Welding Society, 550 N.W. LeJeune Rd., Miami, Florida 33126; OSHA Safety and Health Standards, 29 CFR 1910, available from the U.S. Government Printing Office, Washington, DC 20402.**

First Aid: If contact in eyes, flush immediately with clean water for at least 15 minutes. If swallowed, induce vomiting. Never give anything by mouth to an unconscious person. Call a physician.

DO NOT REMOVE THIS LABEL.

FIGURE 3-11 Warning label for fluxes that contain fluorides.

Everyone knows the risk of remaining in a closed garage with an automobile engine running. This can also be a potential problem with an engine-driven welding machine. The exhaust gas given off by the engine should always be channeled to the outside. In enclosed areas, even large rooms, an engine-driven welding machine, if not exhausted to the outside, can produce a buildup of carbon monoxide and carbon dioxide gas hazardous for people working within the room.

The same problem can occur when preheating weldments using the combustion of fuel gases, coal, or charcoal for heat. The burning of these fuels will produce carbon monoxide and carbon dioxide, which must be exhausted to the outside. Serious harm can happen to the workers which may be undetected by the people in an enclosed area.

A "lookout" or watcher or attendant must be assigned to watch the welders and other workers continually, and to have occasional voice contact with those in the enclosed area. One lookout or attendant should be assigned to a team of welders working in a specific enclosed area. In hazardous cases, lifelines with harnesses should be employed. Lifelines should be attached so that workers can be removed through manholes with ease.

Prior to entering enclosed areas, special precautions should be taken to determine the atmosphere within the enclosed area. Explosive concentrations of gases sometimes build up in an enclosed area. This can occur if an acetylene torch is left inside a compartment, if products of decomposition are enclosed, or from a fuel gas leak into the compartment. The atmosphere within the enclosed area must be tested prior to entering the area. Portable explosimeters are available for sampling the atmosphere to determine if any explosive mixture is present.

Another problem relating to confined or enclosed areas involves oxygen-enriched atmospheres. Such atmospheres can result from the oxy flame cutting torch being left in the compartment and a leak of the oxygen line. Normally, the atmosphere contains approximately 21% oxygen. If the oxygen were to increase by 5% or more, the enriched atmosphere would support rapid combustion or even an explosive mixture. Striking an arc or starting a flame could be extremely hazardous. Clothes, oily cloth, and other combustible items would burn rapidly and create a hazardous condition. Oxygen from a compressed gas cylinder should never be used to help ventilate an enclosed compartment. It should never be used in place of compressed air. Portable instruments indicating oxygen concentration are available and should be used to sample the atmosphere before entering an enclosed compartment.

Oxygen deficiency can be another potential hazard for workers in an enclosed area. When using the gas-shielded metal arc process, the two most popular shielding gases are both heavier than air. Both argon and carbon dioxide weigh approximately 1½ times the weight of air and will displace it. The used shielding gas will in time displace the air so that the atmosphere at the welder's breathing zone will become rich in the shielding gas atmosphere and there would be a deficiency of oxygen. If the oxygen content in the breathing zone is reduced by 5% or more, serious damage can be done to the worker. The atmosphere in an enclosed area must be monitored with a portable oxygen indicator.

Mechanical ventilation must be used for ventilating enclosed areas. Preferably both air exhaust systems and fresh-air supply systems should be employed. When welding, cutting, or allied processes are used in any area that cannot be adequately mechanically ventilated, positive-pressure, self-contained breathing apparatus or air-line respirators must be used.

If you have questions concerning monitoring atmospheres or monitoring instruments, or special breathing apparatus, contact your company's safety department or your local fire department or state industrial commission representative.

Ventilation

Adequate ventilation must be provided for all welding, cutting, brazing, and related operations. Adequate ventilation means sufficient ventilation so that hazardous concentations of airborne contaminants are below the allowable levels specified by OSHA or the American Conference of Governmental Industrial Hygienists (ACGIH). Adequate ventilation depends on the following:

1. Volume and configuration of the space where welding occurs
2. Number and type of operations generating contaminants
3. Allowable levels of specific toxic or flammable contaminants being generated
4. Natural airflow and general atmospheric conditions where work is being done
5. Location of welders and other persons' breathing zones in relation to the contamination, contaminants, or sources

Adequate ventilation for welding can be obtained in three different ways:

1. Natural ventilation
2. General mechanical ventilation
3. Local exhaust ventilation

Natural ventilation occurs when the welding is done out of doors. Natural ventilation occurs indoors if the welding shop is sufficiently large, with a space of 10,000 ft^3 (284 m^3) per welder; if there is a ceiling height of more than 16 ft (5 m) and the welding space does not con-

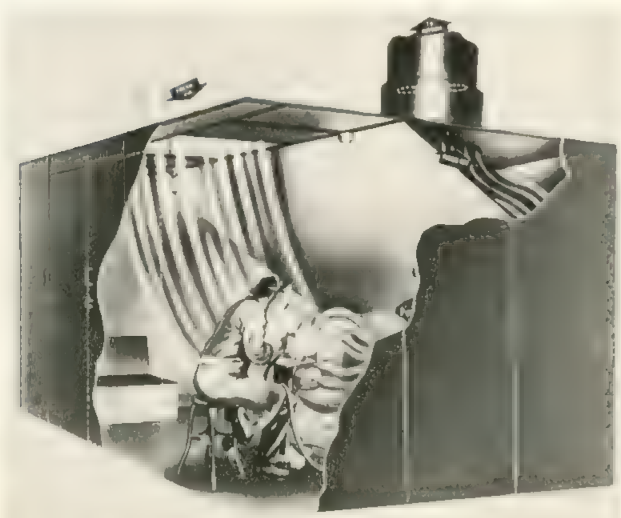
tain partitions, balconies, or other structural barriers that obstruct ventilation; and finally, if the welding is not done in a confined area. Natural ventilation must be supplemented when welding on hazardous materials.

General mechanical ventilation utilizing roof exhaust fans, wall exhaust fans, or similar large-area air movers must be used if the space per welder is less than 10,000 ft^3 (284 m^3), or if the ceiling height is less than 16 ft (5 m) or the shop includes partitions, balconies, or other structural barriers that obstruct cross ventilation. General mechanical ventilation is recommended to maintain a low level of airborne contaminants and to prevent the accumulation of explosive gas mixtures. General mechanical ventilation is used for individual welding booths (Figure 3-12). If general mechanical ventilation is not sufficient to maintain the general background level of airborne contaminants below the limits recommended, local exhaust ventilation or local forced ventilation is required.

Local exhaust ventilation requires the use of fixed or movable exhaust hoods placed as near as practical to the work and able to capture sufficient contaminants to keep the level below the requirements. Local exhaust ventilation can be obtained by four different methods:

1. Use of freely movable hoods (Figure 3-13) placed near the arc.
2. A fixed enclosure with a top and not less than two sides surrounding the welder with a sufficient rate of airflow.
3. Tables with downdraft ventilation of 100 ft^3/min (47 m^3/min) per square foot or square meter of surface area.
4. A low-volume, high-velocity fume exhaust device attached to the welding gun (Figure 3-14). Similar suction devices are available for covered electrode welding.

FIGURE 3-12 Welding booth with mechanical ventilation.



This last system is based on collecting the fumes as close as possible to the point of generation or at the arc. This method of fume exhaust has become very popular for semiautomatic and robotic welding, particularly when using flux-cored welding electrodes. The efficiency of this exhausting system is shown in Figure 3-15, which shows the smoke exhaust gun on and off. This system has proven economical since much less air is exhausted, which reduces the need for massive air makeup units to provide heated or cooled air to replace the air exhausted. In

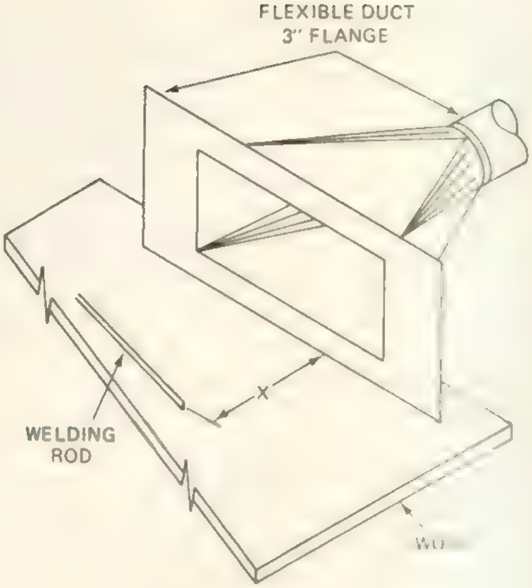
FIGURE 3-13 Local exhaust ventilation using movable hood.

FIGURE 3-14 Local exhaust ventilation using exhaust nozzle on welding gun.

all cases where local exhaust ventilation is used, the exhaust air should be filtered before it is discharged into the atmosphere or returned to the welding shop.

The use of movable hoods for local exhaust systems is explained further by Figure 3-16, which provides more details concerning the nozzle pickup design and airflow velocities to meet exhaust requirements.

FIGURE 3-15 Local exhaust ventilation comparison with and without exhaust.



PORTABLE EXHAUST

X, INCHES	CFM
6	250
9	400
12	1000

AMERICAN CONFERENCE OF
GOVERNMENTAL INDUSTRIAL HYGIENISTS

FIGURE 3-16 Local exhaust ventilation using movable hood design. (From Ref. 20.)

Local forced ventilation means a local air-moving system such as a fan placed so that it moves the air at right angles to the welder across the welder's face. It should produce a velocity of approximately 100 ft/min (30 m/min) and be maintained for a distance of approximately 2 ft (0.6 m) directly across the work area.

Air velocity is relatively easy to measure using a velometer or airflow meter; thus it is easy to check the efficiency of local forced ventilation. Downdraft welding worktables are popular in Europe but have not been used to a very large degree in the United States or other parts of the world.

There is one foolproof method to determine if proper ventilation is being provided. This is done by collecting samples of the atmosphere at the welder's breathing zone under the helmet. A special pickup device mounted inside the helmet is usually used. The atmosphere samples are collected by specialized instruments for a specific period. The samples are then chemically analyzed in calibrated instruments which determine the value of all elements that are found in the welder's breathing zone.

Two welding society documents provide guidance

of making these types of investigations: "Evaluating Contaminants in the Welding Environment, A Sampling Strategy Guide"[21] and "Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes."[22] By comparing the amount of material found and using a factor based on the length of time the sample was taken, it can be determined if the sample meets or exceeds the prescribed limits. The threshold limit values 9 (TLV) (TLV is a registered trademark of the American Conference of Governmental Industrial Hygienists) of most hazardous materials are established by OSHA regulations based on data provided by the American Conference of Governmental Industrial Hygienists' "Threshold Limit Values and Biological Exposure Indices for 1986-1987."[6] The determinations found in the welder's breathing zone should be below these TLV limits. Analytical work of this type must be done only by highly qualified people who are familiar with welding operations, testing and sampling techniques, as well as the analytical methods to determine the amounts of contaminants found in the air samples taken from the welder's breathing zone.

3-5 FIRE AND EXPLOSION HAZARD

A large number of the fires in industrial plants are caused by cutting and welding with portable equipment in areas not specifically designated or approved for such work. The three elements of the fire triangle—fuel, heat, and oxygen—are present in most welding operations. The heat is from the torch flame, the arc, or from hot metal. The fuel is from the fuel gas employed or from combustibles in the welding area. The oxygen is present in air but may be enriched by oxygen used with the fuel gas. Many industrial fires have been caused by sparks, which are globules of oxidized molten metal which can travel up to 40 ft (13 m). Sparks may also fall through cracks, pipe holes, or other small openings in floors and partitions and start fires in other areas which may go unnoticed temporarily.

Hot pieces of metal may come in contact with combustible materials and start fires. Fires and explosions have also been caused when this heat is transmitted through walls of containers to flammable atmospheres or to combustibles within containers. Anything that is combustible or flammable is susceptible to ignition by cutting and welding. Welding or cutting on metal that is in contact with urethane foam insulation is prohibited. All insulating organic foams, whether or not indicated to be fire retarded, should be considered combustible and handled accordingly.

Cutting and welding fires can be prevented by eliminating all combustibles from the welding area. Welding arcs or oxyfuel gas flames rarely cause fires when used in the workshop area designed for welding and cutting. Fire and explosion hazards should be considered from two points of view: welding in designated workshop areas and welding with portable equipment in all other areas.

Work Area

A safe workplace must be provided for welding and cutting operations. Floors, walls, ceilings, and so on, must be constructed of noncombustible materials. The work area must be kept clean and free of combustible and flammable materials. All fuel gas lines, manifolds, branches, and so on, must be installed in accordance with specifications and codes.

Firefighting equipment must be installed in the welding workshop areas. The types of extinguishers for the different types of fires possible should be available and identified for the types of fires that might occur.

Fuel Gases

There are a number of different fuel gases used for welding and flame cutting. The most familiar is acetylene, but propane, natural gas, methylacetylene-propadiene stabilized, and others are also used (see Chapter 14 for details).

Acetylene is sometimes produced on the premises by an acetylene generator. An acetylene generator uses carbide and water to produce acetylene, which is then piped through the plant to the welding and cutting departments. Acetylene generators must be installed properly, maintained properly, and operated only by trained and qualified people. Carbide must be stored properly and never exposed to moisture or water, which creates more acetylene to feed fires.

Acetylene cylinders and other fuel gas cylinders should be stored in a specified well-ventilated area or outdoors away from oxygen and in the vertical position. All cylinders in storage should have their caps on, and both filled and empty cylinders should have their valves closed. In a fire situation special precautions should be taken for acetylene cylinders.[23] All acetylene cylinders are equipped with one or more safety relief devices filled with a low-melting-point metal. This fusible metal melts at about the boiling point of water (212 °F or 100 °C). If fire occurs on or near an acetylene cylinder, the fuse plug will melt. The escaping acetylene may be ignited and will burn with a roaring sound. Evacuate all people from the area immediately. It is difficult to put out such a fire. The best action is to play water on the cylinder to keep it cool and to keep all other acetylene cylinders in the area cool. Attempt to remove the burning cylinder from close proximity to other acetylene cylinders, from flammable or hazardous materials, or from combustible buildings. It is best to allow the gas to burn rather than to allow acetylene to escape, mix with air, and possibly explode.

If the fire on a cylinder is a small flame around the hose connection, the valve stem, or the fuse plug, try to put it out as quickly as possible. A wet glove, wet heavy cloth, or mud slapped on the flame will frequently extinguish it. Thoroughly wetting the gloves and clothing will help protect the person approaching the cylinder. Avoid getting in line with the fuse plug, which might melt at any time.

Apparatus

Gas welding or cutting apparatus must show the approval of an independent testing laboratory. When ordering gas welding or cutting apparatus, specify that it must carry the Underwriters' Laboratories (UL) or Factory Mutual Engineering Corporation (FM) seal of approval.

Gas apparatus must be properly maintained and repaired by qualified people. All too often apparatus is allowed to deteriorate before maintenance is performed. Pressure gauges, welding regulators, welding torches, welding tips, and so on, should all be carefully inspected periodically and maintained at the first sign of deterioration. Oil or grease should never be used on any gas welding or cutting apparatus.

Only approved gas hoses should be used with oxy-fuel gas equipment. Single lines, double vulcanized, or double or multiple stranded lines are available. The double vulcanized or twin hose is preferred. The size of hose should be matched to the connectors, the regulators, and torches. In the United States the color green is used for oxygen, red for the acetylene or fuel gas, and black for inert gas and compressed air. The international standard calls for blue for oxygen and orange for the fuel gas. The connections on hoses are right-handed for inert gases and oxygen, and left-handed for fuel gases. The nuts on fuel gas hoses are identified by a groove machined in the center of the nuts. Hoses should be inspected periodically for burns, worn places, or leaks at the connections. They must be kept in good repair and should be no longer than necessary.

Hot Work Permits

Welding permits, or as they are sometimes called, "hot work permits," are required by some specifications or companies. These permits must be used when welding or flame cutting is done on items that involve hazards. One of the more common uses of the work permit is when welding on aircraft. Special precautions such as making out of the welding permit, the stationing of a fire watcher or lookout with proper fire control equipment, and the signing on and off of the welding operation are prescribed. Other types of operations require hot work permits. These are outlined in the instructions given by the National Safety Council for "Hot Work Permits."[24] Their sample permit form is shown in Figure 3-17. Instructions and precautions against fire appear on the reverse side. Your casualty insurance company may have similar tags. The National Fire Protection Association in its specifications for cutting and welding processes[25] also recommends the use of a hot work permit. A welding permit or hot work permit should be used when portable welding or flame cutting equipment is used for maintenance welding in plants where combustible materials are present, on construction equipment in the field, on aircraft, on ships, and on any other type of potentially hazardous operations. When using portable equipment, these are invaluable and can avoid headlines stating that the fire was caused by "a welder's torch."

Welding on Containers

Any container or hollow body, such as a can, a tank, a hollow compartment in a weldment, or a hollow area in a casting, even though it may contain only air, must be given special attention before welding. The heat from welding will raise the temperature of the enclosed air or gas to a possible dangerously high pressure so that the part or container may explode. Always vent confined air before welding or cutting on a hollow area. Hollow areas may also contain oxygen-enriched air or fuel gases, either of which is extremely dangerous when heated or exposed to an arc or flame.

Explosions and fires may result if welding or cutting is done on empty containers that are not entirely free of combustible solids, liquids, vapors, dust, and gases. Containers can be made safe for welding or cutting by following prescribed steps. Refer to the welding society's "Recommended Safe Practices for the Preparation for Welding and Cutting of Containers and Piping That Have Held Hazardous Substances."[26] No container should be considered clean or safe until proved so by tests. Cleaning the container, which is normally made of metal, is necessary in all cases before welding or cutting. Cleaning should be done by experienced personnel familiar with the characteristics of the contents. Cleaning should be done outdoors; if this is impractical, the inside work area should be well ventilated so that flammable vapors will be quickly carried away. Drain all material from the container and remove sludge, sediment, and the like. Dispose of residue before starting to weld or cut. Identify the material that was in the container and match the cleaning method to the material it contained previously. If the material is water soluble, the container can be cleaned with water. If the material is not readily soluble in water, the container should be cleaned by a hot chemical solution or by steam. Mix the chemicals for cleaning in hot water and pour into the container, fill the container completely with water, introduce live steam to heat, and agitate the solution. If hot water and steam are not available, the cold water method can be used; however, it is less effective, and agitation should be handled by means

PERMIT NO. ______

For electric and acetylene burning and welding with portable equipment in all locations outside of shop.

Date ______________________

Time Started ______________ Finished ______________

Building ______________________

Dept. ______________ Floor ______________

Location on Floor ______________________

Nature of Job ______________________

____

Operator ______________________

Clock No. ______________________

All precautions have been taken to avoid any possible fire hazard, and permission is given for this work.

Signed ______________________
Foreman

Signed ______________________
Safety supervisor or plant superintendent

____

PERMIT NO. 10534

Date ______________________

Bldg ______________________ Floor ______

Nature of Job ______________________

Operator ______________________

____

INSTRUCTIONS TO OPERATORS

This permit is good only for the location and time shown. Return the permit when work is completed.

PRECAUTIONS AGAINST FIRE

1. Permits should be signed by the foreman of the welder or cutter and by the safety supervisor or plant superintendent.
2. Obtain a written permit before using portable cutting or welding equipment anywhere in the plant except in permanent safe-guarded locations.
3. Make sure sprinkler system is in service.
4. Before starting, sweep floor clean, wet down wooden floors, or cover them with sheet metal or equivalent. In outside work, don't let sparks enter doors or windows.
5. Move combustible material 25 feet away. Cover what can't be moved with asbestos curtain or sheet metal, carefully and completely.
6. Obtain standby fire extinguishers and locate at work site. Instruct helper or fire watcher to extinguish small fires.
7. After completion, watch scene of work a half hour for smoldering fires, and inspect adjoining rooms and floors above and below.
8. Don't use the equipment near flammable liquids, or on closed tanks which have held flammable liquids or other combustibles. Remove inside deposits before working on ducts.
9. Keep cutting and welding equipment in good condition. Carefully follow manufacturer's instructions for its use and maintenance.

FIGURE 3-17 Hot work permit. (From Ref. 24.)

of compressed air. Another way of cleaning the container is to fill the container 25% full with cleaning solution and clean thoroughly. Following this, introduce low-pressure steam into the tank, allowing it to vent through openings. Continue to flow steam through the tank for several hours. None of these cleaning methods is perfect, and after cleaning, the tank should be inspected to determine that it is thoroughly clean. If it is not, continue the cleaning operation.

After the container is cleaned, close all openings and after 15 minutes test a sample of the gas inside the container. Use a combustible gas indicator instrument. If the concentration of flammable vapors in the sample is not below the limit of flammability, repeat the cleaning operation. When it is determined that the gas or air inside the container is safe, the container should be so marked, signed, and dated. Even after tanks have been made safe they should be filled with water, as an added precaution before welding or cutting. Place the container so that it can be kept filled with water to within a few inches of the point where welding and cutting are to be done. Make sure that the space above the water level is vented so that the heated air can escape (Figure 3-18).

As an alternative to the water-filling method, fill the container with an inert gas. Flammable gases and vapors will be rendered nonflammable and nonexplosive if mixed with a sufficient amount of inert gas. Nitrogen or carbon dioxide is normally used. The concentration of flammable gases and vapors must be checked by testing as mentioned previously. The inert gas concentration must be maintained during the entire welding and cutting operation. Hot work or welding permits should be

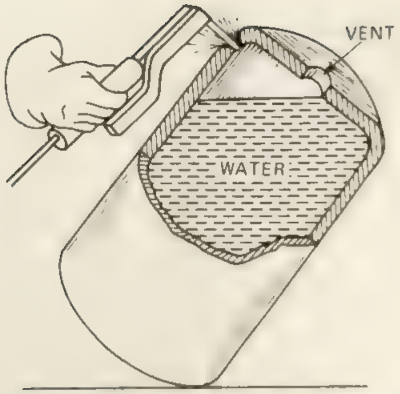


FIGURE 3-18 Safe way to weld containers that hold combustibles.

utilized for all welding or cutting operations on containers that have held combustibles.

Hot Tapping

In pipe lining, welders sometimes do hot tapping. This is the welding of a special fitting to a line carrying a combustible liquid or gas, then cutting a hole in the pipe after the fitting has been welded to it. This must be done by experienced people using special equipment with proper precautions. Before attempting such work, refer to the American Petroleum Institute (API) publication "Welding or Hot Tapping on Equipment Containing Flammables."[27]

3-6 COMPRESSED GASES HAZARD

All compressed gas cylinders are potential hazards. The major hazard is the possibility of sudden release of the gas by removal or breaking off of the valve. Escaping gas that is under high pressure will cause the cylinder to act as a rocket, smashing into people and property. Escaping fuel gas can also be a fire or explosion hazard.

Treatment of Gas Cylinders

Gases used for welding—fuel gases, oxygen, or shielding gases—are normally delivered in cylinders which are manufactured and maintained by the gas supplier in accordance with the regulations of the U.S. Department of Transportation (DOT). In Canada the Board of Transport Commissioners for Canada has this responsibility. In most countries there are laws and regulations concerning manufacturing, maintaining, and periodic inspection of portable cylinders for the storage and shipment of compressed gases. All compressed gas cylinders must be legibly marked to identify the gases contained by either the chemical or the trade name of the gas. There is no international uniform color coding for identification purposes; however, some countries have standardized color marking systems. There is a uniform standard for connection threads in North America in accordance with the American-Canadian Standard "Compressed Gas Cylinder Valve Outlet and Inlet Connections."[28]

In North America the authorities require that a cylinder be condemned when it leaks or when internal or external corrosion, denting, bulging, or evidence of rough usage exists to the extent that the cylinder is likely to be appreciably weakened. Always inspect cylinders for suspicious areas and report this or any damage done to a cylinder to your gas supplier.

Cylinder Storage

Oxygen cylinders should be stored separately from fuel gas cylinders and separate from combustible materials. Store cylinders in cool, well-ventilated areas. The temperature of the cylinder should never be allowed to exceed 130 °F (54 °C). Cylinders should be stored vertically and secured to prevent falling. The valve protection caps must be in place. When cylinders are empty they should be marked empty and the valves must be closed to prohibit contamination from entering. When the gas cylinders are in use a regulator is attached and the cylinder should be secured by means of chains or clamps. Cylinders for portable apparatuses should be securely mounted in specially designed cylinder trucks. Cylinders should be handled with respect. They should not be dropped or struck. They should never be used as rollers. Hammers or wrenches should not be used to open cylinder valves that are fitted with hand wheels. They should never be moved by electromagnetic cranes. They should never be in an electric circuit so that the welding current could pass through them. An arc strike on a cylinder will damage the cylinder, causing possible fracture and requiring the cylinder to be condemned and removed from service.

Oxygen

Oxygen is one of the most common gases carried in portable high-pressure cylinders. It should always be called "oxygen," never "air." Combustibles should be kept away from oxygen, including the cylinder, valves, regulators, and hose apparatus. Oxygen cylinders or oxygen apparatus should not be handled with oily hands or oily gloves. Oxygen does not burn but will support and accelerate combustion of oil and grease and other hydrocarbon materials, causing them to burn with great intensity. Oil or grease in the presence of oxygen may ignite spontaneously and burn violently or explode. Oxygen should never be used in any air tools or for any of the

purposes where compressed air is normally used. Escaping oxygen can enrich the work area, especially enclosed areas, and be a fire or explosion hazard.

Fuel Gases

There are a number of fuel gases and their properties are given in Chapter 14. All are compounds of carbon and hydrogen. All fuel gases are potentially hazardous and should be treated with respect.

When welding or cutting with oxygen and fuel gases, the welder should be particularly alert to backfires and flashbacks. A **backfire** is a loud noise associated with the momentary extinguishment and reignition of the flame at the torch tip. This is caused by obstructing the gas flow, by an overheated tip, or by a damaged tip. If this occurs the equipment should be shut down immediately and corrective action taken. A **flashback** is the burning back of the flame into the tip or torch or even the hose if an explosive mixture is present in one of the lines. It is sometimes accompanied by a hissing or squealing sound and the characteristic smoky or sharp-pointed flame. When this occurs, the equipment should be shut down immediately and corrective action should be taken. Flashback can be caused by improper pressures, distorted or loose tips or damaged seats, kinked hoses, clogged tips, damaged tips, and so on.

In extinguishing the oxygen fuel gas flame the proper sequence is first to close the torch oxygen valve and then the torch acetylene or fuel gas valve. In starting a torch, it is always proper first to open the fuel gas valve and with a spark lighter to light the torch, followed by opening the oxygen torch valve.

Shielding Gases

Shielding gases are either inert or active. True inert gases are argon and helium and are stored in high-pressure cylinders. Nitrogen, considered inert in some cases, is also stored in high-pressure cylinders. These cylinders must be treated with the same precautions as those used with oxygen cylinders. The active gas normally used for weld shielding is carbon dioxide (CO_2). It is stored as a liquid but gasifies upon release. More information is given in Chapter 14.

3-7 WELD CLEANING AND OTHER HAZARDS

The slag that often covers the deposited weld metal must be removed. Welds are often chipped and ground. Hand and power tools are employed and the materials removed are propelled through the air to become potential hazards. Safety glasses with side shields should be worn under the welding helmet.

Radioactive Hot Areas

Welders may be required to work in radioactive "hot" areas. This is due to repair and maintenance operations necessary in nuclear power plants. In such cases, extra-special care and precautions must be observed to determine the radiation levels, time of exposure, radiation protection, and all other factors involved. The exposure time may be extremely short, and welders may be used to setting up automated welding devices and then leaving the hot area to operate the devices remotely. Only qualified personnel with knowledge of working in and around radioactive areas should be permitted to make judgments of this type.

Noise

Weld chipping and weld peening produce excessive noise and should be controlled. Excessive noise can damage hearing and cause other injury. Noise exposure can cause either temporary or permanent hearing loss. The requirements of OSHA regulation prescribe allowable noise exposure levels. Carbon arc air gouging at high currents produces large amounts of noise and ear protection is required. Plasma arc cutting with high current also creates excessive noise and ear protection is required. Figure 3-19 shows a worker wearing suitable ear protection for noisy

FIGURE 3-19 Worker wearing suitable ear protection for noisy work.

work. Noise measurement instruments are available and should be used to check noise in the work area so that precautionary measures can be taken. Normal arc welding operations do not exceed noise-level requirements as specified by OSHA. In combination with other noise-producing industrial machinery, noise levels may be excessive. Noise levels can be measured and monitored by means of specialized instruments. The AWS "Method of Sound Level Measurement of Manual Arc Welding and Cutting Processes"[29] should be consulted. It is necessary that trained personnel be used to measure noise. You can request help from your company's safety department or from the state industrial commission representatives. Noise levels are reduced fairly rapidly as the worker moves farther away from the source of the noise.

Other Hazards

Falling items create hazards. Hard hats should be worn in connection with welding helmets on construction sites and in some plants. Other hazards, such as falling from high places, working with heavy objects, and working around heated metals, are similar to the hazards encountered by all employees in steel plants, forging shops, structural shops, and so on. Welding electrode stubs, the unused ends gripped in the holder, are usually short and round and act as a roller when stepped on at the wrong angle. Electrode stubs should be placed in containers and not thrown or allowed to remain on the floor or working surface.

3-8 SAFETY FOR SPECIFIC WELDING PROCESSES AND OCCUPATIONS

The previous sections dealt primarily with arc welding and oxyfuel gas welding, cutting, and torch brazing. The other welding and allied processes can be hazardous if safety precautions are ignored. The potential hazards mentioned previously apply to most welding and allied processes since electricity, compressed gases, flames, heated metals, or fumes are usually involved. Specific process applications or welding occupations involve other particular hazards. Each section that relates to a particular process includes specific safety information. The following is an overview of these safety situations.

Underwater welding is the most dangerous welding occupation. Underwater work of any type is dangerous, depending on the working depth. "Welding in the dry," underwater, is welding in an atmosphere which is under pressure that is greater than sea-level atmosphere pressure. Higher operating pressures create special hazards. The hazards of underwater welding in the wet in contact with the water or in a habitat are very complex and are mentioned only briefly here. More complete information concerning all aspects of underwater welding is provided in Section 26-5.

Robotic and automated welding are becoming more popular. Robot welding combines the potential hazards of welding with the hazards of moving metalworking machinery. Robots operate outside their machine base area. They involve unanticipated motion, may start unexpectedly, and operate at relatively high rates of speed. Robots are normally safe since operators work outside the operating envelope of the robot. However, when programming robots or maintaining equipment, or troubleshooting welding problems, people work in close proximity to the robot's welding torch and are thus exposed to potential hazards. More information on robotic arc welding is presented in Section 12-7.

Automated brazing and soldering involves motion equipment with the associated hazards. However, fluxes and filler metals employed may give off noxious fumes when heated, especially when heated to temperatures normally above operating temperatures. Adequate mechanical ventilation should be provided for all automated brazing and soldering operations to remove explosive or toxic gases. In addition, large quantities of liquid-heated flux or filler material metal create hazards. Guarding of motion devices must be properly designed and always in place.

Resistance welding operations involve some potential hazards. These are largely involved with motion, since it is present with resistance welding equipment. Special dual palm buttons are normally used to provide operator safety. Operators should wear face shields, spectacles, or goggles to protect the face and eyes from flying sparks that may be ejected from the spot weld area.

Air arc cutting and gouging and plasma arc cutting at high currents create noise of a level that may be harmful. Ear protection should be worn.

Electron beam welding is an automated process, but the motion is normally enclosed. In most cases a vacuum is involved with the welding chamber and normal precautions are required. In high-voltage electron beam systems, x-rays are generated as electron beam strikes the workpiece. Adequate shielding must be provided to protect the operator from x-rays.

Thermal spraying involves potential hazards in addition to those involved with arc welding and oxyfuel gas welding. These involve the use of powders or wires which are atomized and sprayed on the workpiece. Large amounts of particulate matter are produced, which can create problems. Additional information is provided in Section 9-3.

Laser welding is usually an automated operation. Lasers are used not only for welding but also for cutting and surface metal treatment. The equipment must definitely be installed in accordance with the manu-

facturer's recommendations. Certain classes of lasers generate radiation which can produce eye damage. This also relates to reflected laser light. Safety precautions are required which require the use of special glasses and other protective materials.

Continued attention to safe practice is required for all welding, cutting, and allied processes. Common sense and the adoption of practices recommended in this book will help provide a safe workplace.

QUESTIONS

3-1. Why wear safety glasses?

3-2. What is advantage of a curved-front helmet?

3-3. Should oxygen or fuel gas be turned on first when lighting a flame cutting torch?

3-4. Is welding more dangerous or less dangerous than other metalworking jobs?

3-5. Why shouldn't a welder open up the case of an arc welding machine?

3-6. Which is more dangerous, welding open-circuit voltage or the voltage in an electric drill?

3-7. Why is eye and skin protection required against an electric arc?

3-8. Name the metals that create hazards when welded.

3-9. What is an oxygen-deficient atmosphere? How is it related to welding?

3-10. Why is it dangerous to weld on a closed tank or can?

3-11. Give two reasons for checking an enclosed area before welding in it.

3-12. What is the purpose of a hot work permit?

3-13. What should you do if an acetylene cylinder catches on fire?

3-14. Why is maintenance welding more dangerous than production welding?

3-15. How do you make a tank that has held a combustible safe for welding?

3-16. Why should oil and grease be kept away from pure oxygen?

3-17. What is the purpose of warning labels?

3-18. Why should welders keep out of the plume?

3-19. What causes most fires during machining work?

3-20. What is dangerous about welding in a wet situation?

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4

Welding Occupations, Training, and Certification

OUTLINE

4-1 THE WELDING OCCUPATION

Welders can work practically anywhere from the small shop down the street to the largest factories in the major cities. In manufacturing, welders help build everything from automobiles to the largest earth-moving giants. They help build the space vehicles and millions of other products ranging from oil-drilling rigs to computers. In construction, welders are virtually rebuilding the world, extending subways, building bridges, and so on. They work practically everywhere helping to improve the environment by building and installing pollution control devices, water, and air filters. Welders work in shipyards, since the newer ships are welded, and they work on the farm repairing agricultural equipment. There is no lack of variety of the type of welding work that is done throughout the world.

Welding is a challenging career.(1) Work is done under all kinds of conditions both inside and outside.

Welding is an exacting work; every weld on a nuclear power reactor must be perfect. Welding is interesting work. The actual progress and completion of welds happens before the welder's eyes providing a sense of accomplishment of a job well done. Welding is a rewarding career since welders receive high pay. In factories, the pay of the welder is equivalent to that of a skilled machinist. In the construction trade it is equal to that of the skilled craftsman and in the piping trade it is perhaps the highest.

The U.S. government census figures[2] show that in 1960 there were 360,000 welders and flame cutters employed in the country. In 1970 there were 535,000 welders and flame cutters employed; 5% were women. This amounts to a 50% gain of welders while the population grew only 13.3%. The 1980 Bureau of the Census survey[3] shows a total of 793,000 welders and flame cutters employed. This is a gain of over 40% and exceeded their estimate by over 100,000. The opportunity and challenges are here for skilled welders.

Before seriously considering a career as a welder, you should review all aspects of the work. Working conditions vary considerably and in the construction trades it can be outside work in all kinds of weather many times at high heights and sometimes below the surface of the sea. Often the welder must be a member of a labor organization for the craft with which welding is associated. This may mean an apprenticeship program which can take up to six years. Sometimes when welders are urgently required, apprenticeship requirments are waived and the new welder can become a journeyman quickly. Investigate this factor in the particular field of activity you wish to enter. Since welding is considered a tool of the trade in the construction industry, welders may be called boilermakers, plumber pipe fitters, iron workers, sheet metal workers, and so on, even though their principal occupation is welding.

In manufacturing, the variation of work is not as broad. The work is more repetitive unless it happens to be maintenance and repair welding. The need to weld in unusual positions on a wide variety of materials is normally not required.

The welder's job involves physical activities different from most occupations. The welder must hold a consistent arc and work in awkward and sometimes cramped positions for long periods of time. The welder is exposed to heat, hot metal and sparks, fumes, and so on, while continually watching the arc. Also, the necessary protective clothing requirement should be considered in making a career decision.

The hours of work are the same as for others in the same factory or on the same project. Pay is similar to other skilled occupations either in construction or in manufacturing. Pay is sometimes regulated by the qualification level of the welder. Qualification tests may be required and are of different levels of severity. The most difficult usually qualify welders to work on the higher-paying jobs.

Prospective welders should make field trips to factories and construction sites where welding is being done. You should talk with practicing welders to learn as much as possible about the occupation before making a firm decision to enter it.

Visiting welders at work and reviewing the job of the welder makes you soon realize that the work done by people called welders in different industries and companies, and in different geographical locations varies tremendously. In some production shops, the welder may make the same type of weld on the same part day after day (Figure 4-1). Welders in construction and some industries may find each job totally different. A typical construction job is shown in Figure 4-2 which is on a nuclear piping assembly. Between these extremes there are many variations.

The "Dictionary of Occupational Titles"[4] published by the U.S. Department of Labor lists approximately 22,000 job titles which include over 75 for welding, flame cutting and related work. Job descriptions are written for many of these. An analysis of these has been made to determine the "work performed" by welders and "worker traits" of welders.[5] The work performed by welders and the worker traits of welders include the following:

FIGURE 4-1 Welding on highly repetitive parts (GMAW).

FIGURE 4-2 Welding on nuclear piping (GTAW).

Work Performed

1. Worker function
2. Work fields
   (a) Methods verbs
   (b) Machines, tools, equipment, and work aids (MTEWA)
3. Materials, products, subject matter, and service (MPSMS)

Worker Traits

1. Training time
   (a) General educational development (GED)
   (b) Special vocational program (SVP)
2. Aptitude
3. Temperaments
4. Interests
5. Physical demands
6. Working (environmental) conditions

This analysis revealed that training time for general educational development for welders was average for industrial and construction craftsmen. The training time for specific vocational preparation—that is, welding training—ranged from a minimum of one day to a maximum of four years. Aptitude for welders was validated against actual job performance. This indicated that spatial aptitude, form perception, finger dexterity, and manual dexterity are the most significant for the welder. The temperament of welders was rated by determining a positive preference for 10 different factors. This indicated that welders have a preference for activities dealing with things and objects and for activities that are carried on in relation to processes, machines, and techniques.

The physical demands on welders are related to strength, climbing or balancing, stooping, kneeling, crouching, or crawling, reaching, handling, fingering, or feeling, talking and hearing, and seeing. The information determined that welders are involved with heavy work and in some cases moderate work. Seeing is involved in all welding except for the helper and the production line welder. This is one factor that is so important to most welders because of the need to continually watch, observe, and see the weld as it is being made. Depth perception is especially important. People with depth-perception problems rarely become good welders.

Finally, the working or environmental conditions were checked. These data show that welders work inside primarily on the factory-type jobs and both inside and outside for construction-type jobs. It shows that all welders are exposed to certain hazards and these are similar with other metalworking occupations. Finally, it shows that all of the welder occupational titles surveyed are exposed to fumes with the exception of the spot welder.

Fortunately, in the United States, the State Employment Services, in cooperation with the Department of Labor, provide a trade aptitude test program. Anyone seriously interested in a career in welding should visit a local office of the State Employment Service and request to take the General Aptitude Test Battery.

Scores for spatial aptitude, form perception, finger dexterity, and manual dexterity should be well above the minimum. However, it is felt that a strong desire to become a welder may overrule all aptitude tests.

The job of the welder, the flame cutter, and the welding operator represents by far the greatest percentage of jobs in the welding field. There are other opportunities in welding that should be considered. One is the welder-fitter, whose job involves layout or setup work. The applicant must have the skills of the welder, but must also be able to plan and set up work to be welded by the use of fixtures, instructions, and blueprints. Another is the welder who specializes in a particular area, such as working on difficult-to-weld materials. Welders also supervise arc welding robots. The people best qualified to program robots are skilled welders. Programing automated welding equipment and robots is a very gratifying and interesting occupation.

The job of the welder is a worthwhile occupation and a rewarding one. It can be used as a stepping-stone to many other careers.

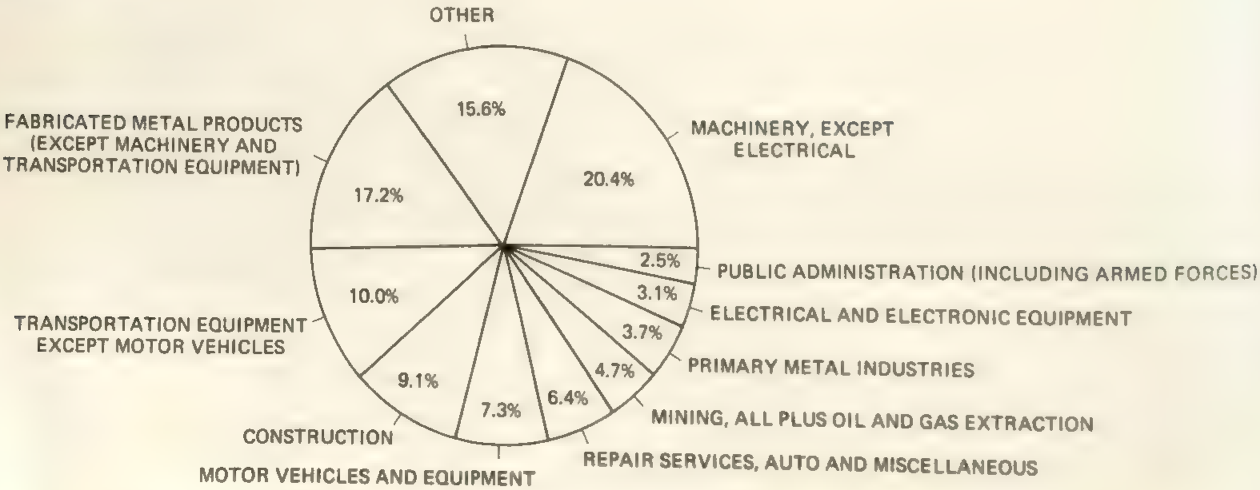
4-2 WHERE WELDERS WORK

The application of welding is practically unlimited. Welding is used everywhere. Almost everything we use in our daily life is welded or is made by equipment that is welded. It is used by all industries that use metal and many that do not. The relative amount of welding used by different industries can be estimated based on U.S. government population statistics. The government population figures show the number of welders and flame cutters employed by industry groups according to their Standard Industrial Classification (SIC).[6] This classification system is used to provide categories, which are groups or establishments engaged primarily in welding or servicing the same or similar products. The number of welders and flame cutters, and the percentage employed by these different industry groups, are based on recent population data[7] provided by the U.S. Department of Labor (Figure 4-3). The figure gives the rank order of the amount of welding done within the different industrial groups. Figure 4-4 is a graphic presentation showing the percentage of welders and flame cutters employed by each group. The rank order of industries is based on the assumption that the greatest amount of welding is done by the industry groups that employ the largest number of welders. These numbers and the industry rankings is ever-changing, based on business and economic conditions. Note in Figure 4-3 a comparison with the rank order of 1970. The assumption that the most welding is done where the most welders are

FIGURE 4-3 Number of welders and flame cutters employed, by industry groups in 1984. (From Ref. 7.)

		Welders and Flamecutters			
Rank	Industry Grouping and Definition	SIC Number	Percent of People	Number of People	1970 Rank
1	Machinery, except electrical	35	20.4	116,508	2
2	Fabricated metal products (except machinery and transportation equipment)	34	17.2	98,154	1
3	Transportation equipment, except motor vehicles	372–379	10.0	57,114	5
4	Construction	15–17	9.1	52,041	3
5	Motor vehicles and equipment	371	7.3	41,667	4
6	Repair services, auto and misc.	75–76	6.4	36,537	9
7	Mining plus oil and gas extraction	10–14	4.7	26,961	11
8	Primary metal industries	33	3.7	21,261	6
9	Electrical and electronic equipment	36	3.1	17,841	7
10	Public administration (including armed forces)	91–97	2.5	14,307	?

FIGURE 4-4 Welders and flame cutters employed, by industry groups.



employed can be slightly misleading since there are many persons in industry and construction who do welding but are not classified as welders. They may be classified as boilermakers, iron workers, plumber pipe fitters, and so on. Additionally, the category flame cutter involves the oxygen-flame cutting process but may not involve actual welding. The increasing trend toward welding automation may also have effects on these data.

Each of the industry groups shown uses welding extensively, but in different ways under different working conditions on different metals, and under different codes and specifications. The largest number of welders (20.4%) is employed by the group known as "machinery, except electrical." This group includes manufacturers of agricultural machinery; construction, mining, and material handling equipment such as power shovels, bulldozers, cranes, and so on; metalworking machinery such as press brakes, punches, and overhead cranes; food-processing machinery; textile and woodworking machinery; papermaking and printing machinery; and office machinery. These products are normally not built to specific codes or specifications, but usually to company standards. Most of these products are made of steel, utilizing plates, shapes, and castings as well as bars and sheet metal. Figure 4-5 shows a heavy machinery base being welded on a positioner.

The second-largest number of welders (17.2%) is employed by the "fabricated metals products" group. This industry group includes manufacturers of pressure vessels, heat exchangers, tanks, refinery equipment, plate trusses, machine bases, sheet metal work, prefabricated metal buildings, and architectural and ornamental work. Most of the welding done by this industry group is governed by codes and specifications. A typical application is a large tank being welded (Figure 4-6). Sheet metal work or welding of thinner gauge material is not governed by the same codes, but is included within this standard industrial classification group.

FIGURE 4-5 Power shovel frame being welded.

FIGURE 4-6 Welding on large tank.

The third-largest number of welders (10%) is employed by the manufacturers of transportation equipment except motor vehicles. This group includes shipbuilding and boat building, the aircraft and spacecraft industry, the railroad equipment industry, and others. The welding done by this diverse group is all somewhat different. In general, ship welding involves plate and structural work and is governed by strict codes for both government and commercial ships. Figure 4-7 shows welding on a ship hull. Aircraft welding is governed by government and military standards. These are very, very strict and involve much testing and qualification work. The work involves welding on diverse items such as aircraft tubular frames (Figure 4-8) and the welding of large external liquid fuel tanks made of aluminum for the space program. Welding in the railroad equipment industry for rolling stock is regulated by codes as well. A welder working on a railroad boxcar is shown in Figure 4-9.

The fourth-largest number of welders are employed by the "construction" industry, which employs 9.1% of the welders and flame cutters. This group includes contracting companies that build tunnels, subways, dams, hydroelectric projects, powerhouses, chemical plants, and structural steel for bridges and buildings, and the welding contractors at the construction site, welding under all types of conditions. Much of this work involves structural welding, which is covered by code. Figure 4-10 shows a typical field-erection welding operation on a large steel frame building. This SIC group also includes piping contractors. Pipe welding is very specialized and is governed by different codes specific to the application. The different types of pipe welding are covered in Chapter 25. A power piping assembly being welded is shown in Figure 4-11.

FIGURE 4-7 Welding on a ship hull.

FIGURE 4-8 Welding tubular frame for airplane.

FIGURE 4-9 Railroad box car being welded.

FIGURE 4-10 Welding on high-rise building.

The fifth-largest number of welders (7.3%) is employed by the "motor vehicle and equipment" group, which is the major segment of the transportation industry. This group includes companies that manufacture automobiles, trucks, buses, trailers, and associated equipment. Traditionally, this industry has been a major user of welding. The product is not governed by a welding code, and in general involves welding of thinner materials, usually on a mass-production basis. This industry uses semiautomatic and robotic arc welding to a very large degree. Figure 4-12 shows semiautomatic welding on an auto-body line.

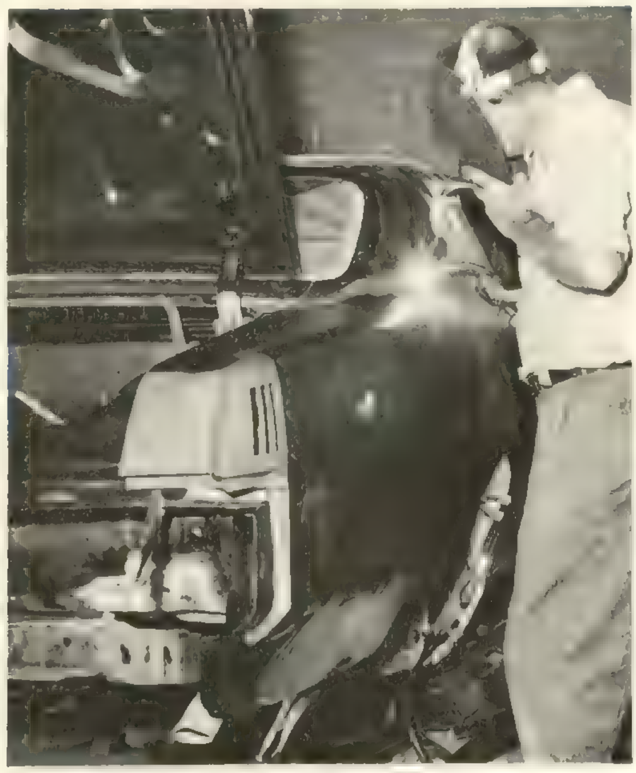
The sixth-largest group of welders (6.4%) belongs to the group "repair services, automobile and miscellaneous." The repair services group is involved almost entirely with maintenance, repair, and overhaul welding. A portion of this is done on auto-body repair work based on collision repair (Figure 4-13). However, much of the repair welding is done on the repair and maintenance of industrial equipment, electrical machinery, repair of worn parts, and so on.

The seventh-largest number of welders (4.7%) is employed by the mining industry and the oil and gas extraction industry. This includes the mining, both deep shaft and open pit, of metal ores and coal. It also includes quarrying of stone, sand and gravel, and clays. A major portion of this industry group involves drilling and extracting oil and gas. A typical repair welding operation is shown in Figure 4-14.

FIGURE 4-11 Pipe work welding in powerhouse.

FIGURE 4-12 Welding on automobile body.

FIGURE 4-13 Auto-body repair welding.



The eighth-largest number of welders (3.7%) are employed by the group "primary metal industries." These industries include steel mills, iron and steel foundries, smelting and refining plants. These companies produce steel plate and structural shapes, tubular products, sheet metal, and castings of all commercial metals. Most of the welding in this group is for maintenance and repair work

FIGURE 4-14 Weld repair on bulldozer.

on the facilities; however, a portion of it is for repair or reclamation welding of castings.

The ninth-largest group of welders (3.1%) is employed by the group "electrical and electronic equipment." This group includes companies that produce electrical generators, transformers, switchgear, electric motors, welding machinery, battery chargers, and household electrical appliances. Welding done by this group runs from the heaviest to some of the lightest. Welding codes are not normally involved.

The tenth-largest number of welders is employed by the group "public administration." This group would include maintenance welding being done by municipalities, state governments, and so on, which in general would involve maintenance welding of bridges, utilities, and so on. However, this group also includes the armed forces, which are large users of welding, particularly in government shipyards, armories, and so on.

The remaining 15% of the welders and flame cutters are employed by other industries not named above. Probably the least number of people that use welding are artists. The welding they do may not have as great an impact as some of the larger groups, but the products produced have a large impact on the public in general. The largest and most unusual piece of welded sculpture is the 630-ft stainless steel–covered St. Louis arch (Figure 4-15). The arch, an inverted catenary curve designed by Eero Saarinen, was built by Pittsburgh–Des Moines Steel Company for the Jefferson National Expansion Historical Association. Direct metal sculptures can be made from different metals and utilize the more popular welding processes. There are many welded fountains and sculptures. One of the more popular artists is George Tsutakawa. A 25-ft fountain made of silicon bronze and copper nickel is shown in Figure 4-16, as well as the welding involved.

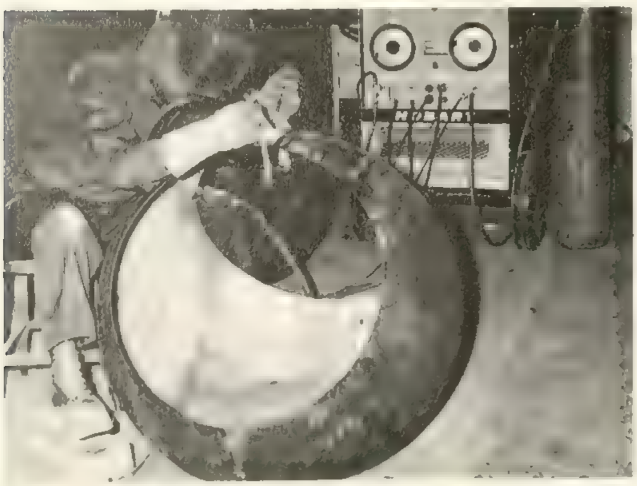
It is interesting to note the geographical location of welders and flame cutters. The largest number of welders are employed in the Great Lakes area. Pennsylvania ranks third, with 6.7% of the welders; Ohio is fourth with 6.3%; Michigan fifth with 5.9%; Illinois sixth with 5.5%; New York eighth with 3.7%; Indiana ninth with 3.5%; and Wisconsin tenth with 3.0%. Despite this, Texas ranked first with 9.0%, and California ranked second with 7.5% of the total. The ranking changes from year to year depending on the business climate in each state.

The major metropolitan areas in rank show Detroit first, Los Angeles/San Diego second, Chicago third, Houston fourth, followed by Philadelphia ranked fifth, Dallas/Forth Worth ranked sixth, Pittsburgh ranked seventh, St Louis ranked eighth, New York City ranked ninth, and New Orleans ranked tenth.

It can thus be seen that welders work all over the country in industries doing metal work.

FIGURE 4-15 The St. Louis arch. (From Ref. 8.)

(a)



(b)

(c)

(d)

(e)

FIGURE 4-16 Direct metal sculpture: Tsutakawa fountain.

4-3 WELDER TRAINING PROGRAMS

Welding training with emphasis on the manipulative skills is provided by a wide variety of training programs. Welding is taught in high schools, trade, vocational, technical schools, colleges, universities, joint apprentice training schools, in-plant or company schools, and armed forces schools, among others.

There are many different types of welding programs available. These range from short adult evening courses designed to provide the minimum skill sufficient to strike an arc and make a simple metal project, to in-depth courses which provide the student with sufficient skill and knowledge to pass difficult qualification tests.

The objective of a training course must be clearly established. A vocational course has the objective to develop entry-level skills for a particular type of work. Unfortunately, in the field of welding it is difficult to define entry-level skills since there are so many different types of jobs requiring different skill levels. Despite this, welding training programs can be analyzed from the student's point of view or designed from the instructor's point of view based on the stated objectives of the course and the skill level expected upon completion.

A vocational program to develop entry-level skills for the arc welder should involve from 250 to 300 hours. This course should cover welding with the shielded metal arc welding process in all positions. It should teach the welding of thin and medium thickness steel using single- and multiple-pass procedures. It should provide training for a variety of electrode types, including the cellulosic, the iron powder, and the low-hydrogen types. Both alternating-current and direct-current welding machines should be used. Related technical topics such as principles of arc welding, welding safety, principles of welding machines, welding electrode identification and selection, weld testing, and inspection would be included. Upon completion of this training program the welder should be able to pass the qualification test necessary for plate or structural welding.

A similar course covering oxyacetylene or oxyfuel gas welding, brazing, and flame cutting should require from 125 to 150 hours. This course should include the assembly of equipment for gas welding, the proper lighting and adjustment of gas torches of different sizes, welding with the torch on thin materials and medium thickness materials in all positions, and the use of filler rod. In addition, it should include brazing using the torch method and flame cutting of steel both manually and with a machine. Related subjects include the principles of combustion of fuel gases with oxygen, the selection of the proper tips for different applications, the adjustment of oxygen and fuel gas for different tips and types of flames, and the selection of filler metals and welding flames. It should include many of the same items for brazing and the setup of equipment and adjustments for flame cutting and the procedures necessary for quality cuts.

These two courses combined should provide entry-level skills for a combination welder. A combination welder should be able to pass the structural test with shielded metal arc welding, the flame cutting tests, and the gas welding and brazing test on various materials.

A vocational training program to train welders to use the gas tungsten arc welding process should require from 60 to 75 hours. The gas tungsten arc welding program should include the use of the process for welding nonferrous materials, particularly aluminum—and also stainless steels and carbon steels. This should be done in all positions utilizing thin to medium thickness materials. Related information should include the principles of the gas tungsten arc welding process, the different equipment required, the construction and adjustment of the welding torch, the selection of shielding gas, the use of high-frequency current, and the selection of filler metal for welding different base metals. Upon completion of this course the welder should be capable of passing appropriate performance tests.

The vocational welding training course for the gas metal arc welding process should require from 60 to 75 hours. This should include the fine wire or short circuiting variation, the spray transfer variation, and could include flux-cored arc welding. This program should include welding of thin materials using the fine wire technique, welding thicker materials with the spray transfer method, and the use of the flux-cored process on heavier materials. It should include welding of nonferrous metals if the student has sufficient skill and ability. The related topics include the principles of the process and its variation, the different equipment that is required, including the principle of constant-voltage power supplies and wire feeders. It should also cover the selection of filler metal and welding shielding gas. Upon completion of this program the welder should be able to pass appropriate performance tests for thin and medium thickness metals in all positions.

The programs cited above are vocational in nature, and upon successful completion the welder should have the necessary skill and ability to be employable in the average fabrication plant. These programs can be supplemented with additional programs for specific welding techniques, such as pipe welding with uphill or downhill travel, welding thin-wall tubing, welding nonferrous materials to aircraft quality standards, and welding with the plasma arc process.

In many situations the time available for such thorough training is not available. In view of this, the programs can be abridged to provide training in fewer processes or with types of electrodes or filler metals or on fewer types of base metals in less varied thicknesses, and may be on only one or two positions. Courses can

also be reduced if the skill required is restricted to specific applications which are repetitive day after day.

The American Welding Society provides a booklet entitled "Minimum Requirements for Training of Welders,"[8] which outlines minimum programs similar to those mentioned above. For more exhaustive programs, refer to the book "Recommendations for Teaching Welding."[9] Many workbooks and manuals providing specialized welding programs are available.

No matter what type of welding training program is planned it should be presented in the following four steps:

1. *A lecture and discussion prior to each new phase of instruction.* This provides background information. These discussions normally last from 15 to 30 minutes and should include a question-and-answer period. Audiovisuals can be used.
2. *An explanation demonstration.* The demonstration of the particular new training phase is given. This demonstration may be repeated so that there is no question about the technique employed. Specific points should be brought out to make sure that each student completely understands the new phase and techniques involved. Audiovisuals can be used.
3. *Supervised individual practice.* After the discussion and demonstration the trainees go to their individual booths and practice the techniques demonstrated. Instructors should periodically check the progress of each student and correct any faults that might develop.
4. *Periodic practical tests.* At the termination of each particular phase, the student is given a test that covers the technique involved. This should be a practical test on which the student makes the prescribed welds. Test pieces should be prepared and tested by fracturing, bending, cross sectioning, and so on, and evaluated to determine the successful mastery of the phase being tested. Tests such as these are very useful since they help students to overcome the fear of qualification tests that are required many times throughout a welder's career.

Students should also be given training in related subjects and should be tested periodically to determine their understanding of the subjects.

4-4 TRAINING SCHOOL FACILITIES

A well-planned welding training department or school with proper facilities and equipment makes it much easier to provide a successful training program. The well-planned school welding shop must be designed for the safety of the students and to accommodate the number of students that will be enrolled. The following information is presented to assist in planning a welding training facility or assist in remodeling exiting facilities.

1. Determine the welding processes that are to be taught now and that may be taught in the foreseeable future.
2. Determine the number of students to be accommodated now and in the foreseeable future.
3. Determine the number of students that will be in the same specific activity at any one time.
4. Plan for welding shop access from the building for students and others. Plan also for access to the welding shop from the outside for ease of delivery of material, equipment, and so on.
5. Plan areas for the different activities that will be involved, including a classroom, welding demonstration area, welding booths, test areas, storage areas, metalworking area, instructors' offices, and washroom and restroom.
6. The classroom for lectures and discussion should be large enough to accommodate the number of students that will be using it at any one time. It should be possible to darken the room for the use of audiovisual aids. It should include chalkboards, bulletin boards, as well as tables, chairs, and so on. Individual learning carrels may be employed and can be part of the classroom or immediately adjacent to it.
7. The welding demonstration area should be outside the classroom since many welding processes create dust and dirt, which is not desirable in the classroom. The welding demonstration area may be elevated so that students can see welds being made. A different demonstration area should be provided for each welding process being taught.
8. Individual welding stations should be provided for each student for each process. Booths for the arc welding processes should provide shielding to prevent arc rays from coming in contact with others. Oxyacetylene or gas welding stations should not be enclosed. Arc welding and the gas welding processes should not be included in the same booth. Students should not be required to work two in a booth.
9. Space should be allocated for metalworking equipment, including tools for preparation of practice specimens and preparation for test specimens. This can include flame cutting equipment, saws, metal shears, iron workers, grinders, and so on.
10. Space should be provided for weld testing. Equipment should include a bending press with appropriate dies, a fixture for breaking specimens, for cross-sectioning welds, and for tensile testing.

11. Storage space is particularly important for a welding shop. Welding material, projects, working supplies, and materials should have proper storage areas.
12. An office must be provided for the instructors. It should include space for a welding library and for storage of training aids and projection equipment.
13. Sufficient restroom and washroom facilities must be provided. Lockers must be available for students, with a sufficient number provided for the total student enrollment.

In addition to the specific items listed above, there are other general requirements for a welding shop. It should be of fireproof construction throughout and should be planned for ease of maintenance. It should allow for natural light and natural ventilation if at all possible. Proper exhaust ventilation, heating, and air makeup should be provided. If climate dictates, cooling should also be provided. The shop must have adequate utilities, including sewer, hot and cold water, compressed air, and electric power. The electric power requirements for a welding shop are considerably greater than for other shops. This is calculated based on equipment included. Many shops also have gas distribution systems for fuel gas, oxygen, and in some cases, shielding gases. Gas distribution systems must be designed by people experienced in the field, and must meet all applicable codes.

The two books mentioned in the preceding section, "Minimum Requirements For Training of Welders"[8] and the minimum "Recommendations for Teaching Welding,"[9] should be consulted when planning a new shop or a shop remodeling program.

Special precautions should be taken for fire protection. This includes making everything in the welding shop of noncombustible materials but also providing fire extinguishers and other safety equipment. State and local regulations must be followed. Arc welding booths should be at least 5 ft square and should include mechanical ventilation.

The welding equipment for a school shop should be representative of the type of machines used in local industry. They should be of industrial quality with 60% duty cycle or higher. Limited input, light-duty machines are not recommended. The welding equipment should be specified for the welding processes to be taught. Both direct-current and alternating-current machines should be employed for shielded metal arc welding. The equipment should be specified completely, including rated output current and type, output voltage, duty cycle, and NEMA class, primary input voltage, frequency, and number of phases. The transformer and rectifier type power sources are less noisy than motor generators; however, some motor generators should be employed since this type is still widely used in the construction industry.

The gas welding and oxygen cutting equipment should also be of industrial quality and should show appropriate approvals. Sufficient supplies and auxiliary apparatus should be available, including welding tips, hose, regulators, and lighters. Each student should have safety and protective clothing for the process being learned.

Welding instructors should make arrangements for welding materials, including gases for welding, cutting, and shielding; filler metals, including electrodes, rods, and flux; and metal for welding practice. Metals for welding must correspond to the training program. Many companies will cooperate with welding training departments and assist by supplying scrap metal for student use. Maintenance procedures should be established so that all welding equipment is in first-class condition at all times.

The final item required for the welding school shop is furniture or equipment for each workstation. It is difficult to find school shop furniture constructed for heavy-duty welding shop use. Many instructors produce their own in the welding shop. Detailed plans and material lists for weld shop equipment are provided in the book "Recommendations for Teaching Welding."

Welding training aids should be used when they contribute to the program. Training aids include the chalkboard, posters, movies, transparencies, slides and filmstrips, models, workmanship samples, cutaway equipment, and so on. Equipment for using audio and visual aids must be available.

There are many movies available on welding and related subjects. Most are in color with sound. Audio coupled slide and filmstrip presentations are also available. These should be selected with respect to the subject areas being taught and should fit the objectives of the course. TV cassettes are becoming more and more popular. Models of parts, cutaway parts, and so on, are all of value and should be used when appropriate.

Most welding equipment manufacturers and trade associations in the welding industry and in the metals industry provide much of this material. In addition, training aids and programs are available from many publishers. When analyzing training aids make sure that they use correct terminology, feature safety practices, and that they are technically accurate.

4-5 QUALIFYING AND CERTIFYING WELDERS

Becoming a qualified welder is a very satisfying experience. It means that you have made specified welds under specific conditions and that these welds have been prepared and tested and have passed the requirements of a specific specification. Congratulations! You deserve it. Qualification of welders is an extremely technical subject and carries with it certain legal responsibilities. Definitions of some of the terms involved follow: **Welder performance qualification** means "the demonstration of

a welder's ability to produce welds meeting prescribed standards." **Welder certification** means "certification in writing that a welder has produced welds meeting prescribed standards."

Qualification is defined differently in different specifications, but in general the qualification is the ability of an individual to perform to a required standard. It is the demonstration that the welder has the ability to make a weld that meets the standards of the specification involved. It means taking and passing a prescribed practical welding test.

Certification is a written statement stating the fact that the welder has produced welds meeting a prescribed standard. Certification implies that a testing organization, a manufacturer, contractor, owner, or user has witnessed the preparation of the test welds, has conducted the prescribed testing of the welds, and has recorded the successful results of tests in accordance with prescribed acceptance standards.

Welder registration is the act of registering a welder's certification by an appropriate or authoritative group or body. Welders and others sometimes become confused when they encounter the need to weld with a "qualified welder." This confusion is easy to understand and is due to the great number of different codes, specifications, and government regulations with seemingly different requirements applying to welder qualification.

Before a welder can work on products such as pressure vessels, piping, bridges, public buildings, aircraft, ships, and so on, the welder must be qualified. Requirement for qualification is dictated by the specification that governs the product being welded. In addition to specific product specifications, there are legal requirements such as city or state laws and federal government regulations that require all welding to be done by certified welders.

Certification under one code will not necessarily qualify the welder to weld under a different code, even though the tests are similar. Each industry has its own welding requirements; therefore, it is absolutely essential that the applicable code to be used in qualifying the welders.

Welding codes and specifications are written to provide a minimum set of rules for the construction of weldments that will protect the public life and property. Codes or specifications cover welding on the following:

1. Pressure vessels and boilers
2. Nuclear reactors
3. Piping for all applications
4. Buildings and bridges
5. Ships and boats
6. Storage tanks and vessels
7. Railroad rolling stock
8. Aircraft and space vehicles
9. Construction and agriculture equipment
10. Shipping containers, tank cars, and tank trucks
11. Miscellaneous equipment

Many engineering and technical societies have formulated codes and specifications in order to maintain uniformity in the fields they serve. Foremost among these in the welding field are the American Welding Society and the American Society of Mechanical Engineers.

Many trade associations, in order to provide product uniformity, have established standards. Among those issuing welding standards are the Association of American Railroads and the American Petroleum Institute.

Many of the larger cities have codes that regulate welding on buildings and structures erected within their city.

Most of the states and provinces have specifications covering the welding of highway bridges. In addition, many of them also have industrial commissions that issue codes covering pressure vessels and pressure piping. The bridge codes are similar to the AWS structural code and the pressure vessel and piping codes are similar to those of ASME. State-adopted codes have legal status.

Various federal government departments, branches, and bureaus issue specifications. Some involve welding. The Department of Defense issues the military (MIL) specifications. Other standards are issued by the Department of Energy, Department of Transportation, and others. These have legal status.

Many companys manufacture products not covered by a code or specification. To ensure continuing product quality, they issue their own requirements which are becoming more numerous because of product liability needs.

The specifications issued by government bodies are enforceable by law and quite often become contractual requirements. Trade association and engineering society specifications are usually involved in purchase agreements as standards of quality acceptance.

Fortunately, most of the welding codes are similar or have a similar requirement for the welding and testing specimens. They have similar requirements for the welding procedures. However, make sure to consult the specific code under which you are qualifying.

Most of the specifications state that the manufacturer, contractor, owner, or user is responsible for the welding done and that they must conduct tests required to qualify welding procedures used. This responsibility carries the requirement of replacing any work that does not pass inspection or test prescribed by the specification. The contractor, manufacturer, owner, or user is personally unable to observe the work of each and every welder that might be employed. Therefore, they rely on the fact that each welder has passed qualification tests. Contractors, manufacturers, owners, and users must maintain complete records of procedures and test results of

qualified welders and operators. They must also hold and use only as directed various approval stamps.

Welders or welding operators cannot be qualified or certified on their own. Manufacturers, contractors, owners, or users will certify that a welder is qualified based on the successful completion of specific test welds. In some codes, the welder is qualified based on the successful completion of specified tests in that code. In most codes, however, a welding procedure specification must first be established and is proof that the procedure will produce satisfactorily welded joints. Following this, each welder must take a performance qualification test.

Qualifying under one code normally will not qualify under another with a few exceptions. One exception involves certain Navy codes, the Coast Guard code, and the American Bureau of Shipping specifications for the welding on ships. Qualifying for one manufacturer under a specification normally will not qualify you for another manufacturer, with a few exceptions. In the piping field procedures are qualified in the name of the National Certified Pipe Welding Bureau or of local contractor associations. Qualified welders may transfer from one member company to another without requalification in these few exceptions.

A welding procedure specification record requires two signatures, one by the person witnessing welding and testing, and the other by the person employed by the manufacturer, contractor, owner, or user who is responsible. Independent testing laboratories do procedure and performance testing for companies and individuals. This can have an advantage since it eliminates possible bias that might occur. The person responsible for welding must also sign procedure and performance test documents. The ASME Welding Qualification Code rquires the welding of both the procedure and performance qualification tests to be witnessed by the certificate holder. The preparation and mechanical testing may be subcontracted, but full responsibility for all requirements may never be subcontracted.

4-6 TRAINING AND QUALIFYING OTHER WELDING PERSONNEL

Welding Supervisor

Welding supervisors go under many names, but in general they supervise and coordinate the activities of welders. They must aid and assist welders, instruct welders in technique, and judge the work of welders, particularly the quality of welds and weldments. A welding supervisor must have welding experience but need not be the best welder. The supervisor must have knowledge of the processes being used by the people being supervised. Many supervisors are selected from the ranks of welders and are given additional specialized training. This training usually consists of courses on supervision and management, on production control, inspection, cost control and accounting, human relations, and so on. Many part-time training programs are available that provide the principles of supervision. These, plus additional courses appropriate to the company or situation involved, are helpful.

In some situations experienced supervisors not involved with welding are given welding training and assigned to manage welding departments. Sufficient welding skill training for the processes that are involved is required plus background technical information.

Some supervisors are required to pass practical and technical tests in welding plus tests related to supervision and management. In Canada, companies doing fabrication and erection of welded steel structures must obtain and maintain certification.[10] A requirement for company certification is that the welding supervisors must have a thorough knowledge of the company welding procedures and specifications, have a good knowledge of the various welding codes and standards involved, and must have knowledge of the welding processes, welding problems, faults, quality control, inspection methods, and the various types of welding equipment. The supervisor must be able to read drawings and blueprints and interpret welding symbols. Furthermore, it is required that the supervisor show proof of experience or take practical tests.

Australia has a code for certifying structural welding supervisors.[11] This code has a strict requirement of experience and training. It requires that supervisors pass written tests covering the aspects of welding and structural steel work.

Many companies have intensive training programs for welding supervisors which include administering performance tests to welders, training welders, checking fit, examining welds being made, verifying that codes and specification requirements are being fulfilled and making certain that welding procedures are correct, etc. It is obvious that the job of welding supervisor is an important and complex job, extremely worthwhile and absolutely necessary.

Welding Inspector

The welding inspector inspects and tests welded joints for visible defects, correct dimensions, joint strength, weld bead penetration, and conformance with layout print and work order specifications, applying knowledge of geometry, welding principles, and physical properties of the metal. The inspector examines joints to detect flaws such as cracks, spatter, and undercut using a flashlight and magnifying glass, inspects joints for internal defects using nondestructive techniques, tests welds using testing equipment, verifies the alignment and dimensions of product, and sets up machines and fixtures used for work

in progress, marks defective pieces and recommends scrapping or methods for rework, records inspection data, supervises the taking of qualification tests, records data, and may certify results. The inspector also verifies that procedures are in order and appropriate to the work and the specifications.

The American Welding Society has established a procedure for certifying welding inspectors.[12] This requires a record of the inspector's experience and training and a test to determine the person's technical knowledge of welding. It requires the applicant to describe technical welding experience or experience as a welding inspector. Recently, the standard has been revised to include a practical examination with a hands-on portion. The hands-on portion requires the use of instruments, an examination of plastic replicas of simple welds, and the viewing of slides showing radiographs of welds. Figure 4-17 shows the equipment used for this portion of the practical test. Upon successful completion of the test and approval of the application, the welding inspector is certified as qualified by the American Welding Society and is registered at their headquarters.

Most states qualify inspectors for pressure vessel and pressure piping work. These are usually done by the State Industrial Commission in conjunction with the National Board of Boiler and Pressure Vessel Inspectors[13] and casualty insurance companies. The National Board provides training and testing to determine that inspectors have the necessary knowledge and ability. Additionally, there are government inspectors for the U.S. Department of Defense military requirements; various cities have inspectors for structural welding on buildings and bridges, and most state highway departments also have welding inspectors. It is impossible to include all the different types of inspectors and the tests and qualifications that are required. For your particular needs you should contact the organization of interest to determine their requirements.

Welding Technician

Many welding technicians have received specialized training by taking various courses to supplement their knowledge of welding. Most technicians were highly skilled welders who had the desire to take additional training to become a technician. The training should include many subjects available through adult training courses at local schools and colleges, technical society programs, correspondence courses, company-sponsored seminars and courses on subjects that are associated with welding, including drawing and blueprint reading, mathematics, physics, chemistry, metallurgy, business, accounting, and English. More and more technicians are graduates of associate degree programs from technical schools, colleges, and universities. An associate degree is obtained with two years of post–high school study or equivalent on-the-job training. In their work,they apply scientific and engineering knowledge and methods combined with technical skills in support of engineering activities. On the job, they perform semiprofessional engineering and scientific functions normally with general supervision by an engineer. Since the technician works closely with the engineers, the engineering technologist must master the language of engineering, mathematics, science, graphics, communications, and specialized subject matter. The technician must be able to apply theory and use capabilities of skilled craftsmen to achieve practical and economical results. The welding technician works with

FIGURE 4-17 Hands-on test for welding inspectors.

designers to improve the way welding is used on products, machines, structures, and equipment. The technician maintains or improves the properties of metals by the welding processes. The technician must know, understand, and be able to operate processes, procedures, and equipment of the welding industry and must verify the existence of a predetermined quality level. Upon graduation, the employment opportunities of welding technicians are almost unlimited.

Welding Instructor

Welding instructors must have a high degree of welding capabilities. A welding instructor should have the competence to pass qualification tests in the same field of instruction. The instructor must be able to demonstrate welding in front of students and to work with students to correct errors of technique. The instructor must also have the ability to communicate to the students, to relate with them, and to impart welding technical knowledge.

In some states vocational instructors are required to have education degrees. In some vocational schools the college degree requirement is eliminated, but practical experience is required. In many cases, specialized training to help instructors teach is required.

There are other types of welding instructors; for example, instructors who teach welding in industrial arts, vocational agriculture, automotive mechanics, and hobby and craft programs. These instructors may only teach a limited area of welding, but must be knowledgeable in this area. These instructors must be able to communicate, teach, and demonstrate the processes that they teach.

Welding Engineer

The welding engineer applies scientific principles to the useful arts. Normally, the welding engineer is applying several of the sciences simultaneously, and must have knowledge of other engineering fields such as metallurgical, mechanical, electrical, structural, and chemical. The welding engineer is dealing almost exclusively with metals, but needs knowledge of ceramics and chemistry since these greatly influence slags, fluxes, and so on. The welding engineer must know the chemistry of flames and of exothermic welding and stress-relieving techniques. The welding engineer must have an understanding of the basic principles of electricity, electronics, and of the complexities of arcs in gases. This engineer must also have a knowledge of physics with respect to metal transfer, heat flow, conductivity, and so on, since heat is involved in most welding processes. The concepts of welding and weldment design must be well known since weldments are successful or not depending on their design. The service performance of the weldment is a tribute to the skill of the welding engineer. Welding engineers require a baccalaureate degree from a college or university. Few engineering colleges offer welding engineering programs. There is only one baccalaureate program in the United States accredited by the engineering council for professional development. Some universities offer master's and Ph.D. degrees in engineering disciplines intimately associated with welding. Welding engineers with bachelor's degrees and with advanced degrees are in high demand.

Registration of welding engineers is not necessary. However, if the welding engineer is involved with public works, registration as a professional engineer under state law is highly recommended. Engineering certification is provided by the Society of Manufacturing Engineers. Certification can be acquired by taking specific tests and maintaining a program of continuing education.

Welding Sales Representative

Many welding sales representatives learned about welding as welders or technicians. With this practical and technical knowledge of welding they can acquire the necessary product knowledge, sales administration, marketing, accounting, commercial law, and other information necessary to successfully sell welding products. The National Welding Supply Association offers specialized training programs to people wishing to become welding sales representatives. Sales representatives can find employment with national manufacturing organizations or local welding distributors. They can work in almost any part of the country. The remuneration for sales representatives can be very rewarding, depending on individual efforts and successes.

Welding Service Representative

Service representatives help maintain proper operation of welding equipment. They normally represent manufacturers or distributors. Their primary function is to help users diagnose problems that involve the welding equipment and to correct the problem by servicing it in the customer's plant or by taking it to their own service shop for repair. The welding service representative must know and understand welding because often the difficult problems involve both welding and the intricacies of the equipment. Electrical and mechanical knowledge and experience are necessary as well as the ability to use tools and instruments. The ability to read blueprints and electrical schematic drawings and to analyze problems is extremely important. Welding service technicians are in great demand most of the time.

Specialized Training

Many specialized training programs are available for welding and welding-related personnel. These may be available from local educational insititions, local

chapters of technical societies, and equipment manufacturers. Manufacturers of nondestructive equipment such as ultrasonic equipment provide training on equipment of their manufacturer. Manufacturers of robotic equipment provide training on robotic arc welding. In addition, manufacturers of specialized automatic equipment provide courses to acquaint operators and others with proper use of this equipment.

Remember, the welder can be the starting point for any of these different types of work. In every case familiarization with welding is required to function successfully in these related welding jobs.

QUESTIONS

4-1. Where are plants doing welding generally located?

4-2. What products do welders help make?

4-3. What tests can be taken to determine if a person should become a welder?

4-4. Name some of the future jobs open to welders who take extra training.

4-5. Where do welders learn to do construction welding?

4-6. In construction, what job titles may a welder have?

4-7. How does welder's pay compare with others?

4-8. What are the physical demands on a welder?

4-9. Is seeing important for a welder?

4-10. Are manipulator skills important for a welder?

4-11. Who normally programs arc welding robots?

4-12. What type of school must one attend to learn to weld?

4-13. What are the four steps of a welding training program?

4-14. What specifications involve welder qualifications?

4-15. What does a welding inspector do?

4-16. Do welding sales representatives need to know how to weld?

4-17. What is meant by "qualifying a welder"?

4-18. What is meant by "certifying a welder"?

4-19. Are the welding tests of all specifications the same? Explain.

4-20. How can you advance to higher-paying welding-related jobs?

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5

Arc Welding with a Nonconsumable Electrode

OUTLINE

5-1 THE NONCONSUMABLE WELDING ARC

There are two basic types of welding arcs; one uses a nonconsumable electrode and the other a consumable electrode. The nonconsumable electrode does not melt in the arc, and filler metal is not carried across the arc gap. The welding processes that use a nonconsumable electrode arc are: carbon arc welding, gas tungsten arc welding, and plasma arc welding. The main function of the arc is to produce heat. At the same time it produces a bright light, noise, and ionic bombardment that removes the oxide surface of the base metal.

A welding arc is a sustained high-current, low-voltage electrical discharge through a high conducting plasma that produces sufficient thermal energy which is useful for joining metals by fusion.[1] The welding arc is a steady-state condition maintained at the gap between the end of an electrode and a workpiece that carries cur-

rent. Welding arcs range from as low as 1 A to as high as 3000 A and a voltage as low as 10 V to over 40 V. The welding arc has a "point-to-plane" geometric configuration, the point being the arcing end of the electrode and the plane the arcing area of the molten pool. A nonconsumable electrode arc is shown in Figure 5-1. Whether the electrode is positive or negative, the arc is restricted at the electrode and spread out toward the workpiece.

The length of the arc gap is proportional to the voltage across the arc, if other conditions remain the same. If the arc length is increased beyond a certain point, the arc will go out. The arc length for welding is limited to a dimension equal to the electrode diameter, up to about four times the electrode diameter. There is a certain current necessary to sustain an arc of different lengths. If a higher current is used, a longer arc can be maintained.

The arc column is normally round in cross section and is made of two concentric zones: an inner core or plasma and an outer flame. The plasma carries most of the current and has the highest temperature. The outer flame of the arc is much cooler and tends to keep the plasma in the center. The temperature and the diameter of the central plasma depend on the amount of current passing through the arc, the shielding atmosphere, electrode size, and type. The relationship between current and arc voltage is not a straight line. The curve of a nonconsumable arc (Figure 5-2) takes a nonlinear form.[2] In general, the arc voltage increases slightly as the current increases. The voltage is higher for longer arcs and for arcs in a helium atmosphere. The conductivity of the arc increases faster than simply proportionality to current.

The arc occurs when electrons are emitted from the surface of the negative pole (cathode) and flow across a region of hot electrically charged plasma to the positive pole (anode), where they are absorbed.

FIGURE 5-1 Nonconsumable electrode arc.

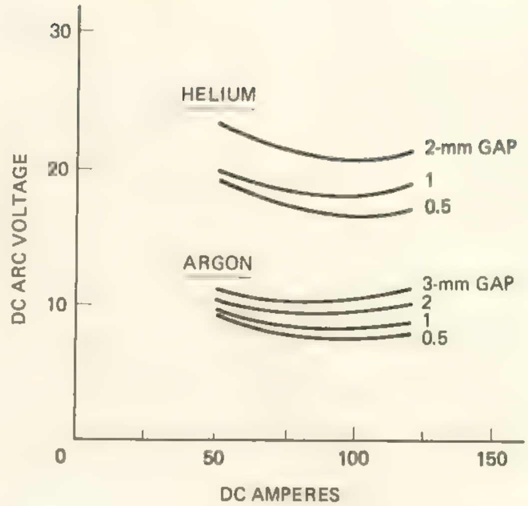


FIGURE 5-2 Arc characteristic volt-ampere curve in argon and helium. (From Ref. 2.)

Arc heat can best be explained by considering the dc tungsten electrode arc in the inert-gas atmosphere (Figure 5-3). In part (a) the tungsten arc is connected for direct-current electrode negative (DCEN). When the arc is started the electrode becomes hot and emits electrons. The emitted electrons are attracted to the positive pole, travel through the arc gap, and raise the temperature of the shielding gas atoms by colliding with them. The collisions of electrons with atoms and molecules produce thermal ionization of some of the atoms of the shielding gas. The positively charged gaseous atoms are attracted to the negative electrode, where their kinetic (motion) energy is converted to heat. This heat keeps the tungsten electrode hot enough for electron emission. Emission of electrons from the surface of the tungsten cathode is known as **thermionic emission**. Positive ions also cross the arc. They travel from the positive pole, the work, to the negative pole, the electrode. Positive ions are much heavier than the electrons but help carry the current flow of the relatively low voltage welding arc. The largest portion of the current flow, approximately 99%, is via electron flow rather than the flow of positive ions. The continuous feeding of electrons into the welding circuit from the power source accounts for the continuing balance between electrons and ions in the arc. The electrons colliding with the work create the intense localized heat, which provides melting and penetration of the base metal.

In the dc tungsten-to-base metal arc in an inert gas atmosphere, the maximum heat occurs at the positive pole (anode).[3] When the electrode is positive (anode) and the work is negative (cathode) (Figure 5-3b), the electrons flow from the work to the electrode, where they create intense heat. The electrode tends to overheat, so a larger electrode with more heat-absorbing capacity is used for

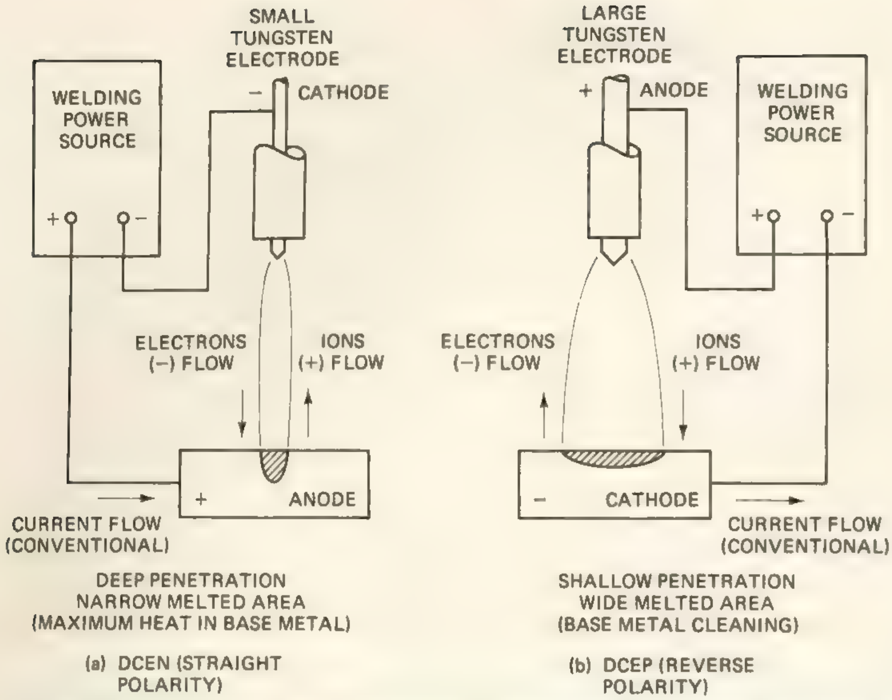


FIGURE 5-3 Nonconsumable arc showing polarity and heat.

DCEP than for DCEN for the same welding current. In addition, since less heat is generated at the work, the penetration is not so great. One result of DCEP welding is the so-called "cleaning effect" on the base metal adjacent to the arc area. This appears as an etched surface and is known as *cathodic etching*; it results from positive ion bombardment. This bombardment also occurs during the reverse-polarity half-cycle when using alternating current for welding.

The arc length or gap between the electrode and the work can be divided into three regions: a central region, a region adjacent to the electrode, and a region adjacent to the work. At the end regions the cooling effects of the electrode and the work cause a rapid drop in potential. These two regions are known as the anode and cathode drop, according to the direction of current flow. The length of the central region or arc column represents 99% of the arc length and is linear with respect to arc voltage. Figure 5-4 shows the distribution of heat in the arc, which varies in these three regions.[4] In the central region, a

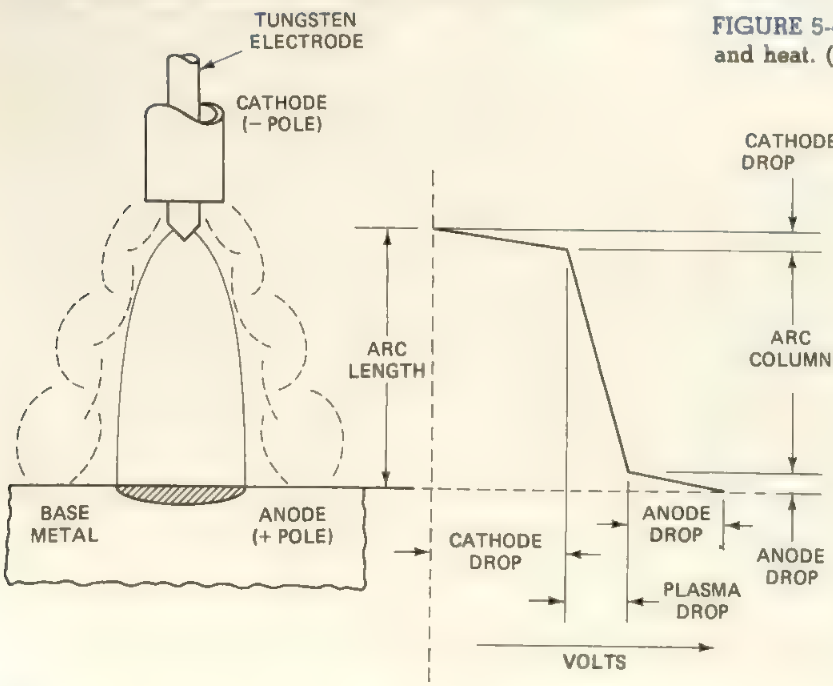


FIGURE 5-4 Arc region versus voltage and heat. (From Ref. 4.)

circular magnetic field surrounds the arc. This field, produced by the current flow, tends to constrict the plasma and is known as the *magnetic pinch effect*. The constriction causes high pressures in the arc plasma and extremely high velocities, and this in turn produces a plasma jet. The speed of the plasma jet approaches sonic speed.

The cathode drop is the electrical connection between the arc column and the negative pole (cathode). There is a relatively large temperature and potential drop at this point. This is the point at which the electrons are emitted by the cathode and given to the arc column. The stability of an arc depends on the smoothness of the flow of electrons at this point. Tungsten and carbon provide thermionic emissions since both are good emitters of electrons. They have high melting temperatures, are practically nonconsumable, and are therefore used for welding electrodes. Since tungsten has the highest melting point of any metal, it is preferred.

The anode drop occurs at the other end of the arc and is the electrical connection between the positive pole (anode) and the arc column. The temperature changes from that of the arc column to that of the anode, which is considerably lower. The reduction in temperature occurs because there are fewer ions in this region. The heat liberated at the anode and at the cathode is greater than that from the arc column. Figure 5-5 shows the approximate temperature in the arc. Arc temperature relates to the location within the arc and to the current in the arc.

In the carbon arc, a stable dc arc is obtained when the carbon is negative. In this condition about one-third of the heat occurs at the negative pole (cathode), the electrode, and about two-thirds of the heat occurs at the positive pole (anode), the workpiece.

Researchers theorized that if the arc column of the tungsten arc could be reduced in cross section, its temperature would increase. If the cross-sectional area of the conducting column is reduced by constricting it, the only way that the same current would still pass is for its conductivity and its temperature to increase. Constriction occurs in a plasma arc torch by making the arc pass through a small hole in a water-cooled copper nozzle. It is a characteristic of the arc that the more it is cooled, the hotter it gets; however, it requires a higher voltage. By flowing additional gas through the small hole, the arc is further constricted and a high-velocity, high-temperature gas jet or plasma emerges. This plasma is used for welding, cutting, and for metal spraying. Its temperature is higher than that of the unrestricted arc.

The thermal energy generated in the arc is the product of welding current and arc voltage. This is the same as any electrical circuit. It is a measure of work that can be performed. The heat is distributed through radiation, convection, and conduction. The heat raises the temperature of the base metal and causes melting, and its effectiveness is related to the arc atmosphere and its thermal conductivity. A low-conductive arc atmosphere will concentrate the heat at the plasma, which produces a high arc density. If the arc atmosphere has a high thermal conductivity, a lower arc density results. Figure 5-6 shows a comparison of a helium-shielded arc and an argon-shielded arc. Note that the helium arc column is larger than the arc column in argon. Note also the deeper penetration with the helium atmosphere.

The voltage of a helium-shielded arc is higher than that of an argon-shielded arc of the same length carrying the same current.[5,6] This is due to the higher ioniza-

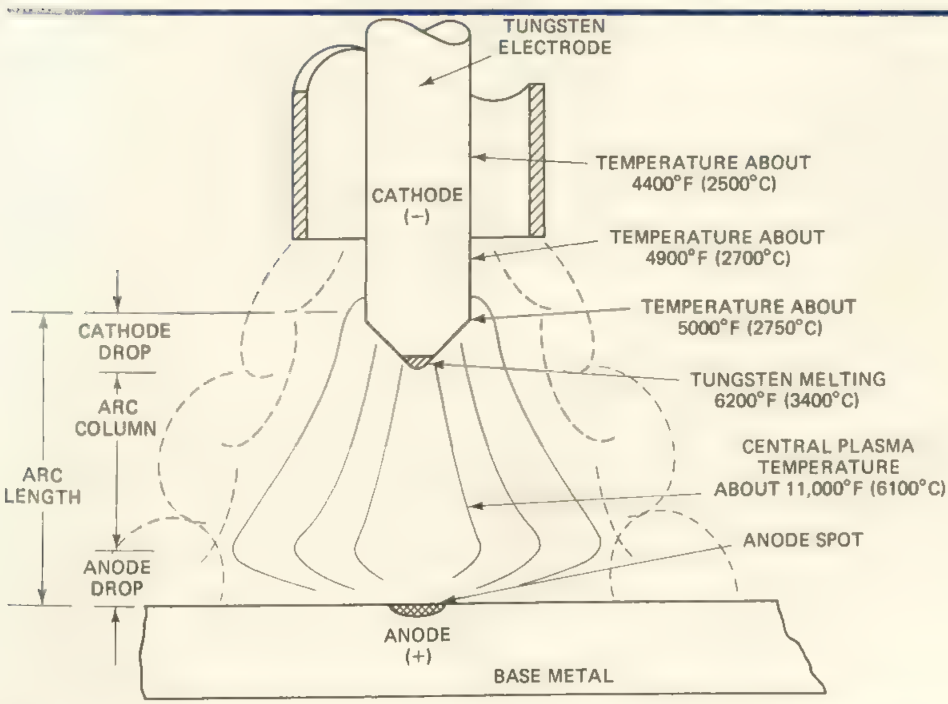


FIGURE 5-5 Temperature of a 100-A dc tungsten arc in argon.

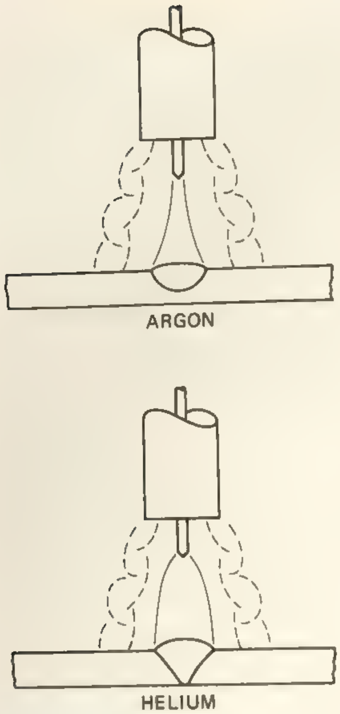


FIGURE 5-6 **Comparison of tungsten arc in argon and helium gas.**

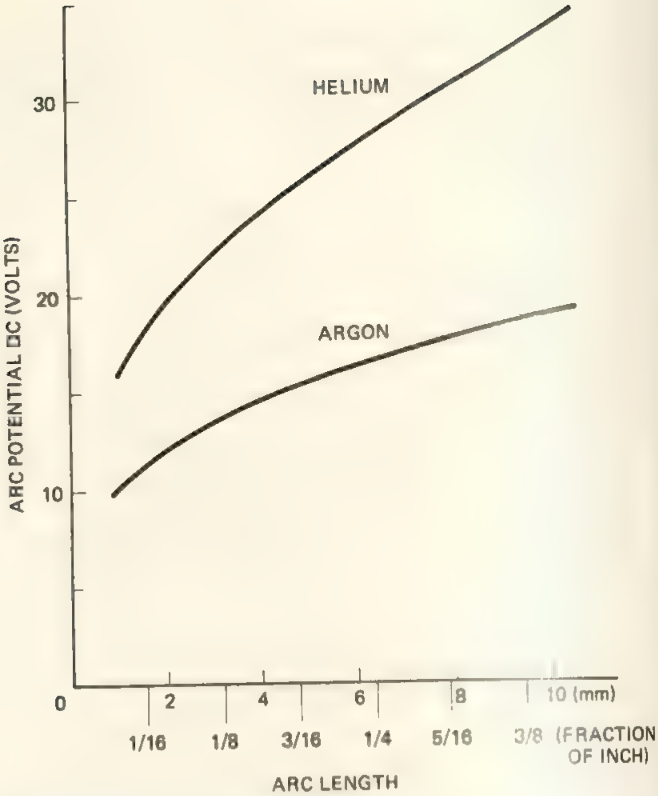


FIGURE 5-7 **Arc voltage–arc length relationship.**

tion potential for helium. For argon it is 15.7 V and for helium it is 24.5 V. The ionization potential is the voltage necessary to remove an electron from the gas atom, making it an ion or charged atom. The difference in arc voltage in the two gases is shown in Figure 5-7, which shows a 300-A arc (DECN) in argon and helium. This explains why the arc shielded with helium has more power (heat) and can do more work. The helium-shielded arc has more penetration, can be moved faster, and can weld heavier base metals. A shielding gas of argon with small amounts of hydrogen or helium can do more work than the 100% argon-shielded arc since it has a higher voltage.

Penetration of the arc depends on a number of factors. The most important is polarity and the second most important is welding current. As current increases and other factors remain constant, the depth of penetration increases. This has a direct relation to the electrode size and tip configuration. The current-carrying capacity of each elecrode size is established; thus a larger elecrode is required for higher current. This really relates to the heat in the arc area, which can also be affected by the temperature of the workpiece. It has been mentioned that higher voltages based on a helium arc produce deeper penetration. The tip configuration is also important; however, this also relates to electrode size. This is because the tip of electrode is usually molten when operated at the optimum current. Hence electrode type (pure or alloyed), electrode cooling, and so on, have an effect.

This brief explanation of the nonconsumable electrode arc just touches on more common knowledge. The tungsten arc has been investigated by many scientists, yet many mysteries remain unanswered, which indicates why the welding arc is such a complicated industrial tool.

5-2 GAS TUNGSTEN ARC WELDING

Gas tungsten arc welding (GTAW) is an arc welding process which produces coalescence of metals by heating them with an arc between a tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture. Both pressure and filler metal may or may not be used. This process is sometimes called *TIG welding*, which indicates "tungsten inert gas welding." In Eurpoe it is called *WIG welding*, using *Wolfgram*, the German word for tungsten.

Principles of Operation

The gas tungsten arc welding process (Figure 5-8) utilizes the heat of an arc between a nonconsumable tungsten electrode and the base metal. The welder's view of the gas tungsten arc is shown in Figure 5-9. The arc develops intense heat which melts the surface of the base metal to form a molten pool. Filler metal is not added when thinner materials, edge joints, flange joints, are welded. This is known as autogenous welding. For thicker materials an externally fed or "cold" filler rod is generally

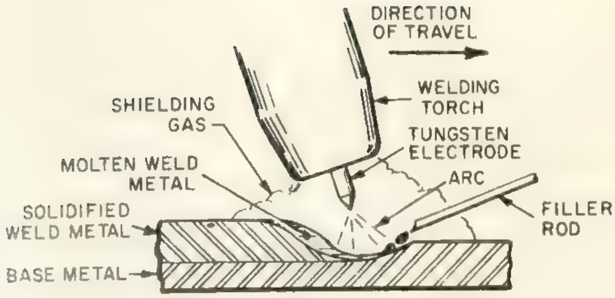


FIGURE 5-8 Process diagram (GTAW).

FIGURE 5-9 Welder's view of gas tungsten welding arc.

used. The filler metal is not transferred across the arc but melted by it. The arc area is protected from the atmosphere by the inert shielding gas, which flows from the nozzle of the torch. The shielding gas displaces the air, so that the oxygen and the nitrogen of the air do not come in contact with the molten metal or the hot tungsten electrode. As the molten metal cools, coalescence occurs and the parts are joined. There is little or no spatter and little or no smoke. The resulting weld is smooth and uniform and requires mimimum finishing.[7]

Advantages and Major Uses

The outstanding features of the gas tungsten arc welding process are:

1. It will make high-quality welds in almost all metals and alloys.
2. Very little, if any, postweld cleaning is required.
3. The arc and weld pool are clearly visible to the welder.
4. There is no filler metal carried across the arc, so there is little or no spatter.
5. Welding can be performed in all positions.
6. There is no slag produced that might be trapped in the weld.

This process allows the welder extreme control for precision work. Heat can be controlled very closely and the arc can be accurately directed. GTAW is used in many welding manufacturing operations, primarily on thinner materials. It is very useful for maintenance and repair work and for welding unusual metals. Gas tungsten arc welding is widely used for joining thin wall tubing and for making root passes in pipe joints. The gas tungsten arc welds are usually of extremely high quality.

The manual method of applying is used for the greatest majority of work. However, both machine and automatic methods are increasingly used. Torches equipped with filler metal wire feed systems are available for semiautomatic welding, but they have limited application. This information is summarized in Figure 5-10.

The gas tungsten arc welding process is an all-position welding process (Figure 5-11). Welding in other-than-flat positions depends on the base metal, the welding current, and the skill of the welder. This process was originally developed for the "hard-to-weld" metals. It can be used to weld more different kinds of metals than any other arc welding process (Figure 5-12).

FIGURE 5-10 Methods of applying (GTAW).

Method of Applying	Rating
Manual (MA)	Most popular
Semiautomatic (SA)	Not popular
Machine (ME)	Popular
Automatic (AU)	Popular

FIGURE 5-11 Welding position capabilities (GTAW).

Welding Position	Rating
1. Flat	A
Horizontal fillet	A
2. Horizontal	A
3. Vertical	A
4. Overhead	A
5. Pipe – fixed	A

Base Metal	Weldability
Aluminums	Weldable
Bronzes	Weldable
Copper	Weldable
Copper nickel	Weldable
Cast iron, malleable, nodular	Possible but not popular
Wrought iron	Possible but not popular
Lead	Possible but not popular
Magnesium	Weldable
Inconel	Weldable
Nickel	Weldable
Monel	Weldable
Precious metals	Weldable
Low-carbon steel	Weldable
Low-alloy steel	Weldable
High- and medium-carbon steel	Weldable
Alloy steel	Weldable
Stainless steel	Weldable
Tool steel	Weldable
Titanium	Weldable
Tungsten	Possible but not popular

FIGURE 5-12 Metals weldable (GTAW).

This process can weld extremely thin metals normally by the automatic method and without the addition of filler metal. Above 0.125 in. (3.2 mm), a joint preparation is usually required; however, this depends on the base metal type and welding position. Also, above this thickness multipass technique is usually required (Figure 5-13).

Joint Design

The joint designs used for gas tungsten arc welding are essentially the same as those used for shielded metal arc and gas welding. Some changes are made, but these are usually involved with different metals or for welding pipe in the fixed position. Joint detail variations for different metals are covered in Chapter 15 and special joints for pipe welding are covered in Chapter 25.

Welding Circuit and Current

Welding circuit for gas tungsten arc welding is shown in Figure 5-14. This circuit diagram shows several optional items. One is the "cold" filler rod, the second is the foot pedal which can be used to regulate the current while welding, and the third is cooling water used for the welding torch, recommended when welding at high-current. Constant current (CC) is used and it may be alternating or direct current. Direct current can be used with either polarity, depending on the job requirements.

The polarity of maximum heat and its relationship with penetration, electrode size, and cleaning action was discussed in the preceding section. Welding with alternating current is very common but presents some difficulties, such as arc instability and arc rectification. The problems and solutions were discussed in the preceding section.

When superimposed high frequency is used with ac gas tungsten arc welding, certain precautions are required. These are necessary since welding power sources equipped with high-frequency spark gap oscillators inherently radiate power at frequencies which may interfere with radio communications and television transmission. In view of this, their operation in the United States is subject to control by the Federal Communication Commission. Most countries have similar regulations.

Welding machines containing high-frequency stabilizers or separate high-frequency stabilizers must be installed with special attention to provide earth grounding and special shielding. Manufacturers provide special installation instructions that limit high-frequency radiation. These instructions require that all metal conductors in the area of the machine must be earth grounded. If these instructions are followed, the user can post a certificate stating that the high-frequency stabilizer may reasonably be expected to meet FCC regulations.

Equipment Required to Operate

The heart of the welding circuit is the welding power source. The constant-current (CC) power source is used for gas tungsten arc welding. The steeper the volt-ampere

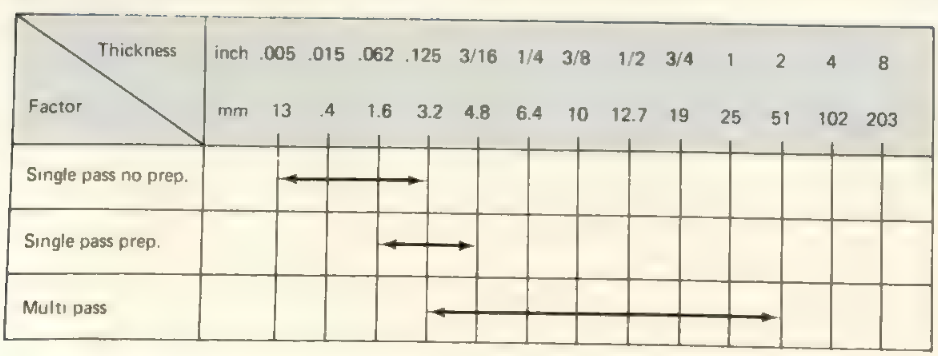


FIGURE 5-13 Base metal thickness range (GTAW).

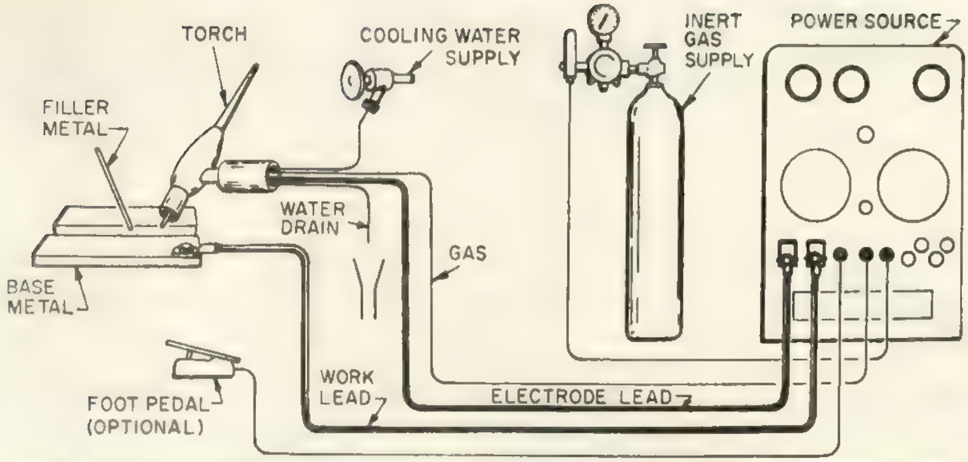


FIGURE 5-14 Circuit diagram (GTAW).

characteristic curve, the more satisfactory the power source. This is because variations in arc length will cause changes in arc voltage but will result in only very small changes in welding current. This is very important for manual welding. Conventional or constant-current welding machines used for shielded metal arc welding can be employed for gas tungsten arc welding. Conventional ac welding machines must be derated 25% due to rectification in the arc. Machines designed for GTAW should be used. These machines include special features, such as high-frequency stability, gas and water valves, and so on, making them more suitable for this process. A typical GTAW welding machine operates with a range of 3 to 200 A or 5 to 300 A with a range of 10 to 35 V at a 60% duty cycle. The newer gas tungsten arc welding machines offer other advantages, such as programmability, remote current control, current pulsing, and so on. This is covered in Chapter 10.

The **torches** used for gas tungsten arc welding are designed and used only for this process. Torches with handles are used with the manual method of applying.

Automatic torches are similar in design but without a handle (Figure 5-15). They are designed to be clamped in a holding bracket. The basic construction is the same. Air-cooled torches, designed for light-duty welding up to approximately 150 A, and water-cooled torches, designed for heavy-duty welding up to 600 A, are available. Figure 5-16 shows manual torches, both the air-cooled and the water-cooled types. A cross-sectional view of a water-cooled manual torch is shown in Figure 5-17. The different types and sizes of welding torches and their capacities are summarized in Figure 5-18. The head angle is measured by the angle between the centerline of the handle and the centerline of the tungsten from the arcing end. Guns are rated by the current-carrying capacity normally at a 100% duty cycle. The inside diameter of a nozzle is given by inches or by numbers that represent eighths of an inch. Welding torch nozzles are available in different materials. Normally a ceramic is used; however, metal nozzles and glass nozzles for visibility, are available.

Special nozzles are available that provide trailing gas shielding for welding titanium and other easily oxidized metals. Devices are also available for providing lamellar shielding gas flow. These are used for welding in deep grooves, on outside corners, or where drafts will disturb the gas shielding. They are not necessary for most welding applications since the torch nozzle must be held close to the work to maintain the necessary arc length. The torches are designed to firmly hold the tungsten electrode, to transmit the welding current to the electrode in the center of the nozzle, and to introduce the inert shielding gas around the tungsten electrode and to direct it to the arc area. Water-cooled torches are more complicated since they provide water passages in the head of the torch in addition to providing the shielding gas and welding cur-

FIGURE 5-15 GTAW torches for automatic welding.

FIGURE 5-16 Manual GTAW torches.

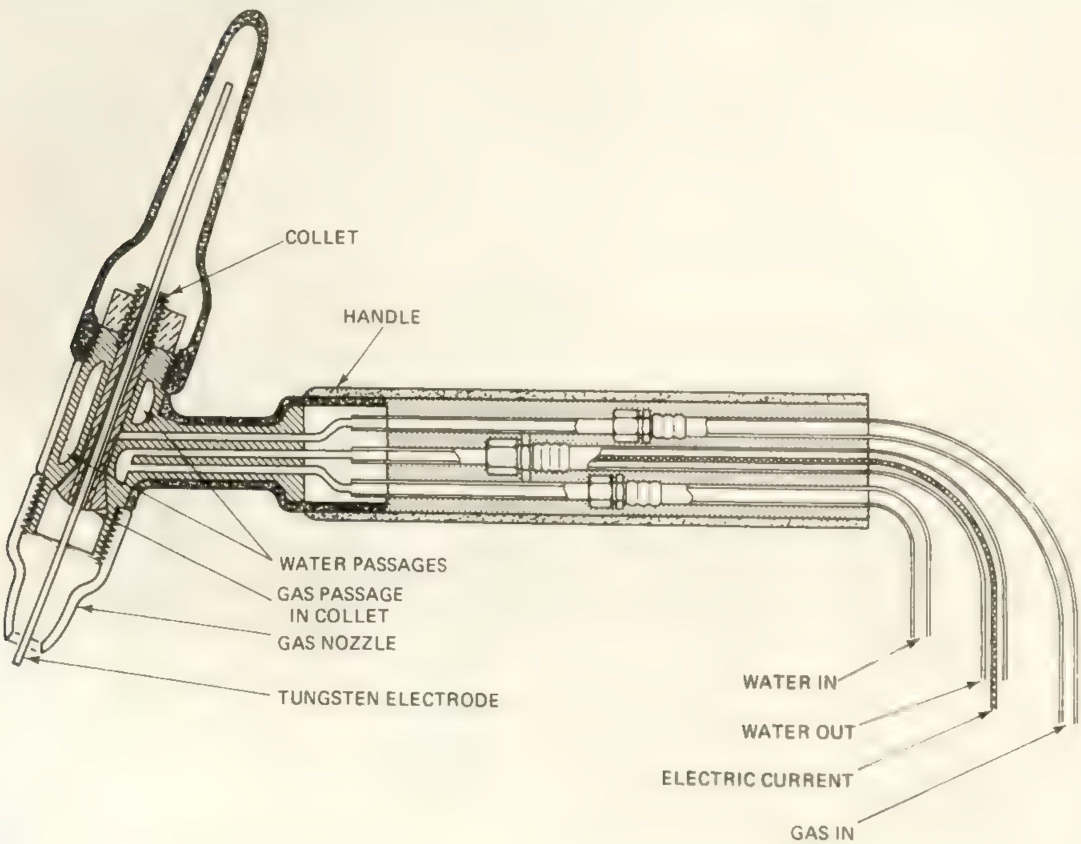
rent. In the water-cooled torch the power cable is enclosed in the return hose for the cooling water. In this way, smaller cables can be used since they are cooled during the operation of the torch. Gas tungsten arc torches come equipped with the necessary hoses and leads attached.

Materials Used

Materials used in gas tungsten arc welding are the filler metal, the shielding gas, and, to a lesser degree, the tungsten electrode. Filler metal is not used when welding extremely thin metals; however, for most applications filler metal is added. The composition of the filler metal should match the base metal. The size of the filler metal rod depends on the thickness of the base metal which usually dictates the welding current. Filler metal is normally added to the pool manually, but automatic feed can be used.

The **electrode** material for gas tungsten arc welding is usually tungsten and tungsten alloys since tungsten has the highest melting point of any metal (6170°F) (3410°C). Four classes of tungsten electrodes have been standardized by the American Welding Society.[8] These four types are shown in Figure 5-19 which also shows the AWS classification and the color code for the tip of the electrode. Tungsten electrodes are available in two finishes:

FIGURE 5-17 Cross section view of water-cooled torch.



Current Capacity 100% Duty Cycle	AC	DC EN	Head Angle	Cooling Method	Nozzle Inside Dia.	Tungsten Dia. in.	mm	Tungsten Length in.	mm	Torch Weight oz	g
50 @ 60%		x	135°	Air	1/4	0.040-3/32	1.0-2.4	1	25.4	3	85
75	x	x	120°	Air	5/16	0.020-1/16	0.5-1.6	3-7	76.2-177.8	4	113.4
100	x	x	120° or 135°	Air	5/16	0.020-5/32	0.5-4.0	2-3-7	50.8-76.2-177.8	4	113.4
150	x	x	120°	Air	5/16	0.020-5/32	0.5-4.0	3-7	76.2-177.8	5	141.75
200	x	x	120° or 135°	Water	5/16	0.020-3/32	0.5-2.4	2-3-7	50.8-76.2-177.8	5	141.75
250	x	x	120° or 135°	Water	3/8	0.020-1/8	0.5-3.2	2-3-7	50.8-76.2-177.8	5	141.75
300	x	x	120°	Water	3/8	0.020-5/32	0.5-4.0	3-7	76.2-177.8	6	170
350	x	x	120°	Water	11/16	0.010-5/32	0.3-4.0	3-6	76.2-152.4	6	170
500	x	x	120°	Water	11/16	0.010-3/16	0.3-4.8	3-7	76.2-177.8	6	170
650	x	x	135°	Water	5/8	1/8-5/16	3.2-7.9	2-1/2	63.5	7	198.45

FIGURE 5-18 Size and capacity of gas tungsten arc welding torches.

FIGURE 5-19 Type, size, and classification of tungsten electrodes.

AWS Classification	Type	Tip Color
EWP	Pure Tungsten	Green
EWTh1	1% Thoria added	Yellow
EWTh2	2% Thoria added	Red
EW Zr	1/2% Zirconia added	Brown
Diameter - 0.020 to 0.250 inch	(0.5 to 6.4 mm)	
Lengths - 3 to 24 inch	(76 to 610 mm)	

standard or ground. The ground finish provides an extremely smooth and perfectly round electrode which is better able to conduct heat from the electrode to the collet of the welding torch. Tungsten electrodes are available with diameters ranging from 0.020 to 0.250 in. (1 to 6.4 mm) and in lengths of 3 to 24 in. (75 to 610 mm).

Of the four types of electrodes, the EWP class is pure tungsten. The other three have alloy added. The EWTh1 has 1% thorium; the EWTh2 has 2% thorium added; and the EWZr has ½ of 1% zirconium added. The addition of thorium and zirconium makes the tungsten alloy better able to emit electrons when hot. It also provides for increased current-carrying capacity of the electrode and provides for a more stable arc and better arc starting.

When installing a new tungsten electrode in the torch the color tip should be at the back end of the torch so that it is not destroyed by the arc. The collet must be the proper size for the tungsten being used. The entire assembly must be tight so that the heat of the arc is transmitted to the torch body where it can be carried away. The EWP or pure tungsten electrodes are the least expensive and should be used for the less critical operations or for general purpose work on different metals. The EWTh1 or 1% thoriated tungsten provides for easier arc starting, gives a more stable arc, and can be operated at slightly higher temperatures. The EWTh2 or 2% thoriated tungsten is even better for arc starting, is more stable, and has a higher current-carrying capacity. EWZr or zirconated tungsten electrodes also provide for longer life and more stable operation. Figure 5-20 gives the continuous welding current range for each of the different types of electrodes related to the electrode size.

Electrode size must always be selected with care and must be related to the type of current, the type of work, and the amount of current that will be used. The amount of welding current required is found in the welding pro-

FIGURE 5-20 Current ranges for tungsten electrodes.

Tungsten Electrode Diameter in.	mm	Continuous Welding Current—Amperes: AC & HF EWP	AC & HF EWTh1 or 2 or EW Zr	D.C.E.N. EWTh1 or EWTh2	D.C.E.P. EWTh1 or 2 or EW Zr
0.020	.5	—	—	5-35	—
0.040	1.0	10-40	15-60	30-100	—
1/16	1.6	30-70	60-100	70-150	10-20
3/32	2.4	70-100	100-160	150-225	15-30
1/8	3.2	100-150	140-220	200-275	25-40
5/32	4	150-225	200-275	250-350	40-55
3/16	4.8	200-300	250-400	300-500	55-90
1/4	6.4	275-400	300-500	400-650	80-125

cedure schedules for welding the particular metal in question. The data provided in these tables constitute the starting point; for example, if a welding current of 100 A is required and alternating current is used, it would indicate that a 3/32-in. (2.4-mm) EWP or pure tungsten or a 1/8-in (3.2-mm) pure tungsten electrode could be used, or if an alloyed electrode were to be used, the 1/16-in. (1.6-mm) or the 3/32-in. (2.4-mm) electrode could be used. If the procedure schedule calls for direct-current electrode negative (DCEN) or direct-current electrode positive (DCEP), different electrode sizes would be needed. Welder preference may also enter into the size selection. Experience is also important; for example, if the welder is using pure tungsten electrode and it tends to become overheated or appears to have a "wet surface," the current is too high for the size of the electrode. When the tungsten has this "wet surface" appearance, it becomes more susceptible to picking up contamination from the base metal. A larger electrode size of the same type should be selected or an alloyed-type electrode of the same size could be used. Too much current or an electrode too small will cause excessive tungsten erosion. Tungsten particles may become deposited in the weld metal.

If the current is too low, or the tungsten electrode is too large in diameter, the arc will wander erratically over the end of the electrode. Grinding the electrode to a point will reduce this problem. It will also help to direct the arc. In general, choose the size of electrode that will be working as close to its maximum current-carrying capacity as possible. The electrode should remain shiny after use and should never be allowed to touch the molten metal. If this happens, it will become contaminated and must be reprepared. The electrode should show a balled end and the balled end should not exceed 1½ times the diameter of the electrode (Figure 5-21). The angle of pointing the electrode should be related to the welding current and the thickness of the metal being welded. It usually ranges from 30 to 120°; 60° is the most common angle.

The **shielding gas** used for gas tungsten arc welding is an inert gas. Only argon and helium are used since the other inert gases are much too expensive for this type of use. Gas selection is based on the metals to be welded. It is necessary to consult the procedure schedule for the particular metal that is to be welded. These tables show the type of gas recommended and the gas flow rate. More information concerning shielding gas is given in Chapter 14. Argon is more commonly used. It is readily available and is heavier than helium and slightly heavier than air, which provides for a more efficient arc shielding at lower flow rates. Argon is better for arc starting and operates at a lower arc voltage. Helium is much lighter than argon or air and thus tends to float away from the weld zone, and higher flow rates are required. Helium provides a higher voltage and more heat in the arc. It is also possible to weld at a higher speed with helium than with

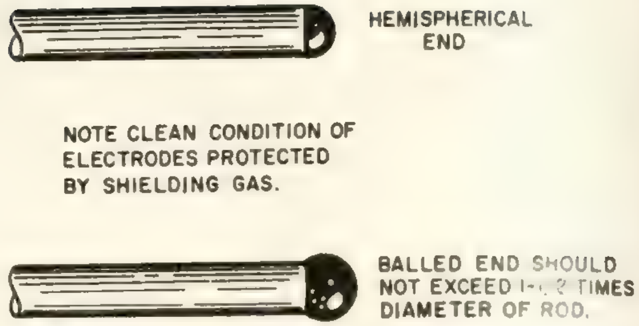


FIGURE 5-21 Tungsten electrode arc end condition.

argon. There are some cases where helium and argon are mixed for the optimum shielding gas for a particular metal or weld schedule.

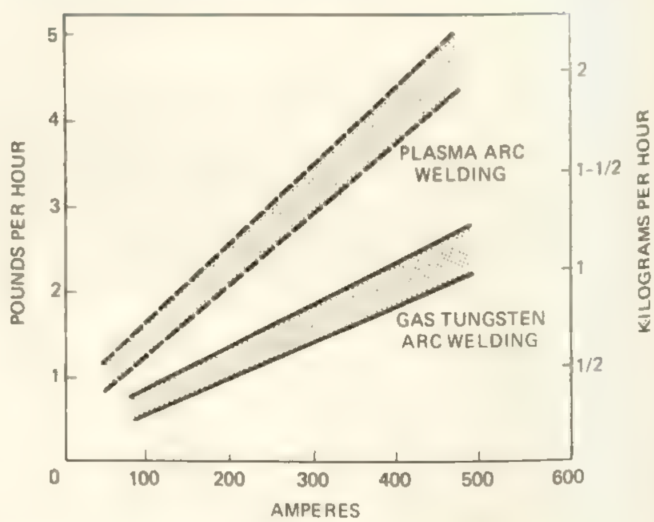
Deposition Rates

The gas tungsten arc is used as a source of heat to melt sufficient base metal and filler metal to provide a manageable weld pool. It is similar to oxyacetylene and carbon arc welding. The gas tungsten arc welding process is not a high-production or high-deposition-rate welding process. The graph shown in Figure 5-22 is a deposition rate curve relating to welding current. This deposition rate is relatively low and this is one reason why gas tungsten arc welding is not used for welding heavy material.

Quality of Welds

The quality of gas tungsten arc welds ranks higher than the quality of any of the arc welding processes. This high level of quality can be obtained provided that all necessary precautions are taken. Since much of the work done by the gas tungsten arc welding process is on nonferrous

FIGURE 5-22 Deposition rate.



metals, it is absolutely essential that cleanliness be considered every step of the way. The work center or work area should be extremely clean. Worktables, fixtures, and so on, should be clean. The gloves used by welders should be clean. Filler metal should be clean, the gas must be welding grade, and the apparatus must be in excellent condition. If these conditions are followed and if the welder has sufficient skill, high-quality welds will result.

Heat input and welder technique has much to do with weld quality. Figure 5-23 shows these factors when welding on aluminum. When the heat input is too low, which can occur from too low welding current or welding speed too fast, the high small bead is evident and penetration is minor. When the welding current is too low, the bead is too high, there is poor penetration, and the possibility of overlapping at the edges. When the welding speed is too fast, the bead is too small and the penetration is minimal. When the heat input is too great, which can occur from too high a welding current or too low welding speed, the bead becomes extremely large, usually wide and flat. There is too much penetration and there may be spatter. When the torch is too far from the work, a long arc occurs, the efficiency of the gas shielding is reduced and poor weld appearance will result, especially in welding aluminum.

Following is a brief discussion of some of the common quality problems and the recommended action to overcome them.

Weld Metal Porosity. Porosity is usually caused by oily, wet, dirty base metal, insufficient inert gas coverage, or dirt and heavy oxide coating on the filler rod. In groove welds there should be backing or purging gas and cleaning of the underside of the groove adjacent to the weld. In the case of aluminum, a stainless steel wire brush or chemical cleaning should be used. Inefficient gas shielding can be caused by side drafts of air which disturb the shielding gas envelope. It may also be caused by leaks in the gas system or it can be caused by impure shielding gas. Equipment should be checked frequently to make sure that the gas system is tight. It is also important that no moisture from cooling water get inside the gas supply hose.

Dirty welds, particularly on aluminum, are another frequent problem. This can result from a problem in the shielding gas supply. There can be a leak in the hose connection, poor-quality shielding gas, an oversize gas nozzle, the nozzle held too far from the work, insufficient gas flow, or anything else that contributes to poor shielding of the arc area.

Poor penetration is primarily a heat input problem and is related to travel speed and welding current to the base metal thickness and conductivity and joint type. Too much amperage will make the bead too flat and rough and may cause cracking. Insufficient amperage will produce an uneven high crown bead. Travel speed also affects penetration. If the speed is too fast, the bead will have a high crown, be rough, and have insufficient penetration. The welding speed may need to be varied or changed, particularly on small weldments where heat buildup occurs. When the base metal is cold, a lower speed is required; as the workpiece absorbs heat and rises in temperature, the speed should be increased.

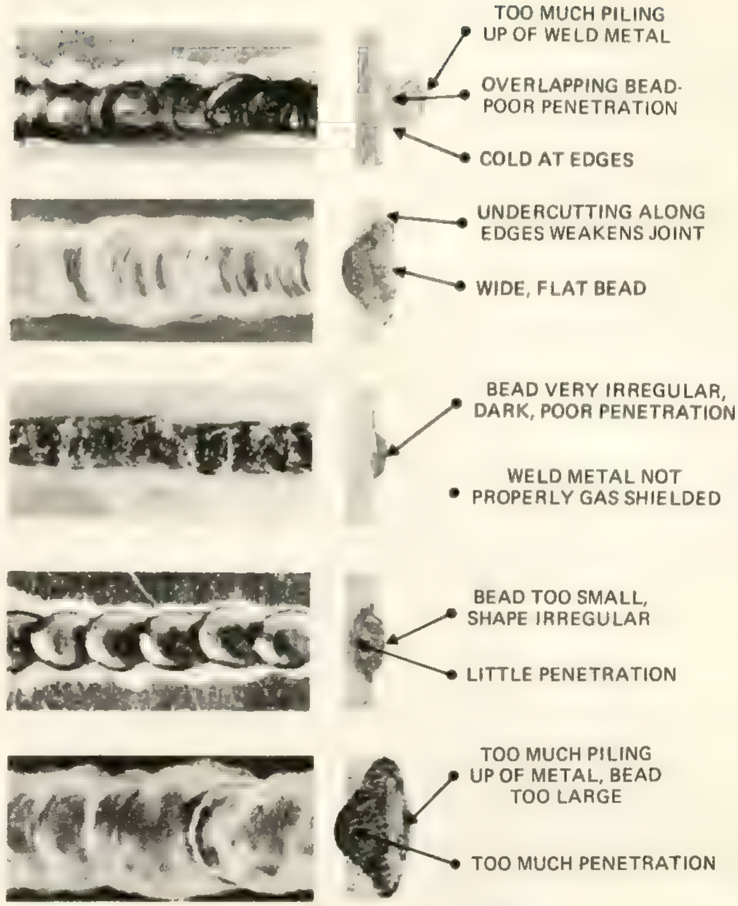


FIGURE 5-23 Quality factors of GTAW welding of aluminum.

A common quality problem is tungsten inclusions in the weld deposit, which can be detected by radiography. This is sometimes called *tungsten spitting* and is based on using too much current for the size or type of the tungsten electrode. The tungsten type may have to be changed or a larger tungsten electrode employed.

Another serious problem is an unstable arc, which is normally a result of a contaminated or dirty electrode. The electrode will become oxidized if the inert gas is not continually surrounding it while it is hot. This is the reason for postflow controls on most gas tungsten arc welding machines. The gas flow should continue after the welding is stopped to keep the tungsten surrounded by inert gas while it is still at an elevated temperature. Another problem can be that the tungsten electrode protrudes too far beyond the end of the gas nozzle. Normally it should not protrude more than $\frac{1}{16}$ in. (1.6 mm).

Postflow should be adjusted for a longer period of time if the tungsten remains dirty. The other problem with tungsten electrodes is the contamination which occurs if the electrode is allowed to touch the molten metal. This will immediately cause the electrode and the arc to become unstable and at that time welding should be stopped and the electrode redressed.

Dirty filler metal with an excessive oxide coating can also create dirty welds. Moisture can occur in this heavy oxide coating. The filler rod should be cleaned with sandpaper.

Welding on dirty, oil-impregnated material, or attempting to repair cracks in machinery parts requires the removal of defective material, thorough cleaning, and preheating to help eliminate any absorbed oil, grease, moisture, and so on.

Water leaks in the torch can usually be detected by coloring of the weld surface. Condensation can occur on the inside of gas hoses and the water vapor in the arc will cause the tungsten to become contaminated.

In summary, quality welds require that all conditions be correct, that materials used be of the correct specification and cleanliness, that the apparatus be in good working order, and that the proper welding technique be employed.

Weld Schedules

For gas tungsten arc welding it is important to establish welding currents based on the type of metal and the weld joint detail. Welding schedule tables are provided in the chapter for the metal being welded. Normal practice is to consult these procedure tables and to establish the welding conditions in accordance with them. Once the welding current level is known, the type of welding current to be used and the type of tungsten electrode recommended, it is then possible to establish tungsten electrode size.

The welding procedure tables shown for the different metals also provide weld travel speed which must be used in determining heat input. Under mechanized conditions the weld speeds can normally be increased over manual application. The feed rate for filler rod is not given since this is a matter of technique for manual welding.

The weld schedules are related to the weld pool that must be carried by the welder. This relates to welding position, type of metal, weld joint detail, and so on. More experienced welders can carry larger molten pools and make welds at a higher speed.

Welding Variables

Gas tungsten arc welding involves a number of variables. Each variable has a specific effect on the weld and there is an interrelationship among variables that affects the final weld. The preselected variables include: tungsten type, tungsten size, nozzle size and gas type. These must be established and are usually part of a welding procedure. The primary variables are welding current, arc voltage, travel speed, pulsing when used, taper, and upslope and downslope, when used, for programmed welding. The secondary variables include rod feed speed when used, torch angles, and possibly tungsten angles. There are other factors that affect the weld quality, and these include clamping, fixturing, heat sinks, heat buildup, backing, purging gas, and high frequency for arc starting.

The factors that are of interest in a weld are penetration of the weld in the base metal, bead width of the deposit, and weld reinforcement or height. It is assumed that weld surface appearance is acceptable and weld metal deposit is of the required quality. It is therefore important to recognize the interrelationship of the primary variables to provide penetration, bead width, and reinforcement. These factors are all influenced by heat input. The effect of travel speed and current was previously mentioned; however, it is important to consider the conductivity of the metal and the heat-sink effect of any fixturing that might be employed.

A major reason for developing pulsed welding was to provide deep penetration, which is obtained from the high current while reducing the total heat input to avoid too much molten weld metal. Programming is also useful, particularly on small welds, where heat buildup can become a factor.

Safety Considerations

The safety factors involved with gas tungsten arc welding are very similar to those involved with the other arc welding processes. The gas tungsten arc seems brighter at the same current than the arc of shielded metal arc welding. This is because the smoke is not present. The brightness of the arc tends to cause air to break down and form ozone. Adequate ventilation should be provided. The bright arc rays cause fumes from hydrochlorinated cleaning materials or degreasing agents to break down and form phosgene gas. Cleaning operations using these materials should be shielded from the arc rays of the gas tungsten arc.

The final hazard is the possibility of displacing the air when welding in enclosed areas such as tanks. Ventilation and other precautions for welding in enclosed areas should be followed.

Limitations of the Process

The major limitation of gas tungsten arc welding is its low productivity. It also has a higher initial cost. The power source and the torch are more expensive. The justification for this is the ability of the process to weld so

many metals in thicknesses and positions not possible by shielded metal arc welding.

Variations of the Process

There are a number of variations of the gas tungsten arc welding process. The more popular of these are:

- Pulsed-current GTAW
- Manual programmed GTAW
- Hot-wire GTAW (automatic)

The most popular variation of this process is known as pulsed-current gas tungsten arc welding. The pulsed-current mode of welding is a way to control heat input. It offers a number of advantages over conventional or steady-current welding as follows:

1. Control molten pool—size and fluidity (especially out of position)
2. Increased penetration
3. Oscillation travel and dwell control
4. Travel speed control
5. Better consistent quality

In conventional GTA welding the amount of welding current at the arc is the same except when it is adjusted by the welding machine rheostat or by a foot-controlled rheostat. The pulsed-current mode provides a system in which the welding current continuously changes between two levels (Figure 5-24). During the periods of high-pulsed current, heating and fusion takes place and during the low-pulse current periods, cooling and solidification take place. It is as if the foot rheostat were moved up and down to increase and decrease the welding current on a regular basis. The newer GTAW power sources provide for high- and low-current periods or pulse current. The machine automatically switches to high current then to low current and will hold each value for a specific time. The pulsed gas tungsten arc can make a weld seam of overlapping arc spot welds. Each arc spot type weld is produced during the high-current pulse time.

FIGURE 5-24 Pulsed current current-time relationship.

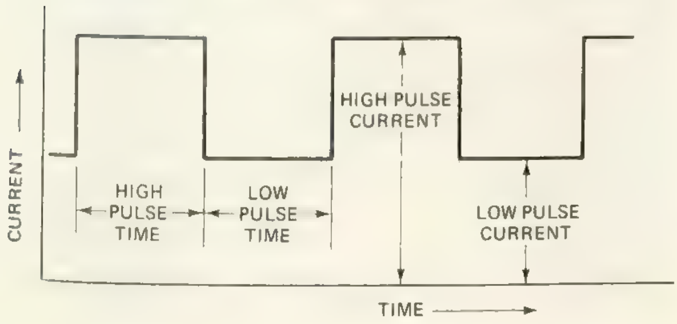


FIGURE 5-25 Pulsed current weld sectional view.

The current then decreases to the "low-pulse current" or background current, which allows the weld to partially cool and solidify while maintaining a low-current consistent arc. The torch is then moved to the next point along the weld joint and held motionless during the next high-current pulse. This sequence of events continues and the weld that is produced is shown in Figure 5-25.

There are four factors that must be controlled to weld with pulsed-current. These four factors are:

1. *High-pulse current* or *pulse current:* the welding current during the high-pulse time period
2. *Low-pulse current* or *background current:* the current during the low-pulse time period
3. *High-pulse time:* the time period of the high-current pulse
4. *Low-pulse time:* the time period of the low-current pulse

Power sources designed for pulsed current welding are equipped with controls to adjust the high- and low-pulse current and time. In general, the high-current pulse should be adjusted to twice or at lease 1½ times the normal steady-state current that would be used for the same job. The low-pulse current is usually only sufficient to maintain a stable arc during the low-current pulse period. This is normally set at 25% of the high-pulse current, or less. For example, if the high-pulse current is set at 200 A and a low-pulse current of 50 A is desired, the percent of weld current should be 25%.

The time period for each pulse is extremely important. The "high-pulse time" is set to allow the formation of the molten pool which has the penetration desired. This may vary from a 0.20 to 1.0 second. The low-pulse time is set sufficiently long to allow the molten pool to partially freeze. With proper adjustments, it is possible to control the weld pool, the size of the weld bead, and the penetration depth in any position on any weldable metal. Initial welding conditions are usually a starting point and the welder will be able to adjust the settings for optimum welding based on the material, its thickness, the welding position, the joint detail, and so on.

The use of pulse-current welding will allow the welder to develop a rhythm of movement. Normal technique is to hesitate during the high-pulse time and move or oscillate with the torch during the low-pulse time. Filler metal is usually added during the high-pulse period. With

additional experience using pulsed current GTA welding, the welder will make the proper adjustments and vary travel speed for consistent high-quality welds. The welder will find that it is easier to do a better welding job with pulsed current than with conventional steady current.

Distortion and warpage are reduced with pulsed current GTA welding on thinner materials. This is due to the lower heat input of the process. Misalignment of joints and the welding of light to heavy sections are made easier with pulsed-current welding. The pulsed current can be adjusted to the point that adequate penetration can be obtained on the heavier section with the high pulse while the low pulse provides the control needed to avoid excessive heating of the thinner member. Pulsed-current welding can be done manually or automatically with or without filler wire. Figure 5-26 shows a weld made in copper using pulsed current.

The programming of weld current is often used in automatic welding and can be used for manual application. Programmers are used to make the welding current rise or fall at specific rates to specific values. A finger switch mounted on the torch will start the preselected program. The torch switch can be used to stop the program or make it repeat. This is known as manual programmed gas tungsten arc welding and is popular for welding tubing and root pass welding of pipe. More information on programmed welding is given in Chapter 12.

The "hot" wire TIG welding variation uses electrical power on the filler metal. The filler rod that is fed into the weld puddle is "electrically" hot compared to the normal filler rod addition which is electrically "cold." The electrical hot wire carries a low-voltage current that preheats the filler rod. It enters the weld pool at an elevated temperature and melts quicker, thus increasing the deposition rate. One of the major applications for the "hot" wire GTAW variation is for weld surfacing, particularly overlaying of stainless steel on low-carbon steel. It is used in the machine and automatic method of applying since the hot wire must always be in contact with the molten puddle in order to conduct the preheating current (Figure 5-27).

Industrial Use and Typical Applications

The use of gas tungsten arc welding is widespread. It is being used to a great degree for welding nonferrous metals. The aircraft industry is one of the principal users of gas tungsten arc welding. Space vehicles are almost all entirely fabricated by the gas tungsten arc welding process. This includes the shells, structures, the various tanks that are required, and the thousands of feet of tubing involved in rocket engines.

Small-diameter thin-wall tubing is almost exclusively welded by this process. Tubes are also welded to tube sheets for heat exchangers with programmed gas tungsten

FIGURE 5-26 Pulsed current weld on thin material.

FIGURE 5-27 Cold wire feed entering weld pool

FIGURE 5-28 Reclaiming cast aluminum housing

arc welding. Another important use of gas tungsten arc welding is the making of root-pass welds in piping—thin and heavy wall, large and small diameter for the process and power industries where high-quality welding is required. Virtually every industry uses GTAW for welding thin materials, especially the nonferrous metals.

The repair and maintenance industry is a major user. Gas tungsten arc welding is used for repairing tools and dies, for repairing cast aluminum and magnesium parts, and for repairing highly critical items. Figure 5-28 shows an example of reclaiming a cast aluminum housing.

5-3 PLASMA ARC WELDING

Plasma arc welding (PAW) is "an arc welding process that uses a constricted arc between a nonconsumable electrode and the weld pool (transferred arc) or between the electrode and the constricting nozzle (nontransferred arc). Shielding is obtained from the ionized gas issuing from the torch, which may be supplemented by an auxiliary source of shielding gas. The process is used without the application of pressure."* The welder's view of the transferred plasma arc is shown in Figure 5-29.

*Unattributed quotations throughout the next several chapters are official AWS definitions.

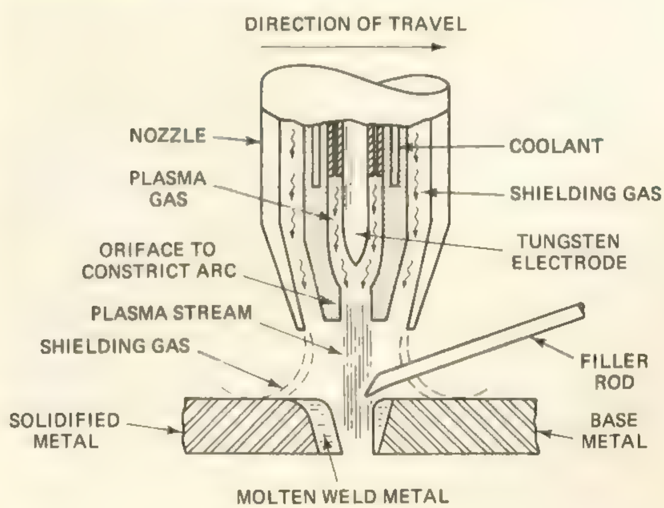
FIGURE 5-29 **Welder's view of plasma welding arc.**

Principles of Operation

The plasma arc welding process (Figure 5-30) is often compared to the gas tungsten arc process because of the many similarities. If an electric arc between a tungsten electrode and the work is constricted or reduced in cross-sectional area, its temperature increases since it carries the same amount of current. This constricted arc is called a plasma and plasma is sometimes called the fourth state of matter.[9] There are two modes of operation, the nontransferred arc and the transferred arc. The **nontransferred mode** means that the current flow is from the electrode inside the torch to the nozzle containing the orifice and back to the power supply. The nontransferred mode is normally used for plasma spraying or for generating heat in nonmetals. The **transferred arc** means that the current is transferred from the tungsten electrode inside the welding torch through the orifice to the workpiece and back to the power supply. The difference between these two modes of operation is shown in Figure 5-31. The transferred arc mode is used for welding except for very low current applications.

The plasma is generated by constricting the electric arc passing through the orifice of the nozzle and the hot ionized gases that are forced through this opening. The plasma has a stiff columnar form and is fairly parallel sided so that it does not flare out in the same manner as the gas tungsten arc. The high-temperature stiff plasma arc, when directed toward the work, will melt the base metal surface and the filler metal that may be added to make the weld. In this way, the plasma acts as an extremely high temperature heat source to form a molten weld pool in the same manner as the gas tungsten arc. The higher-temperature plasma causes this to happen faster. When the plasma is used in this way it is known as the "melt-in" mode of operation. High temperature

FIGURE 5-30 **Process diagram (PAW).**



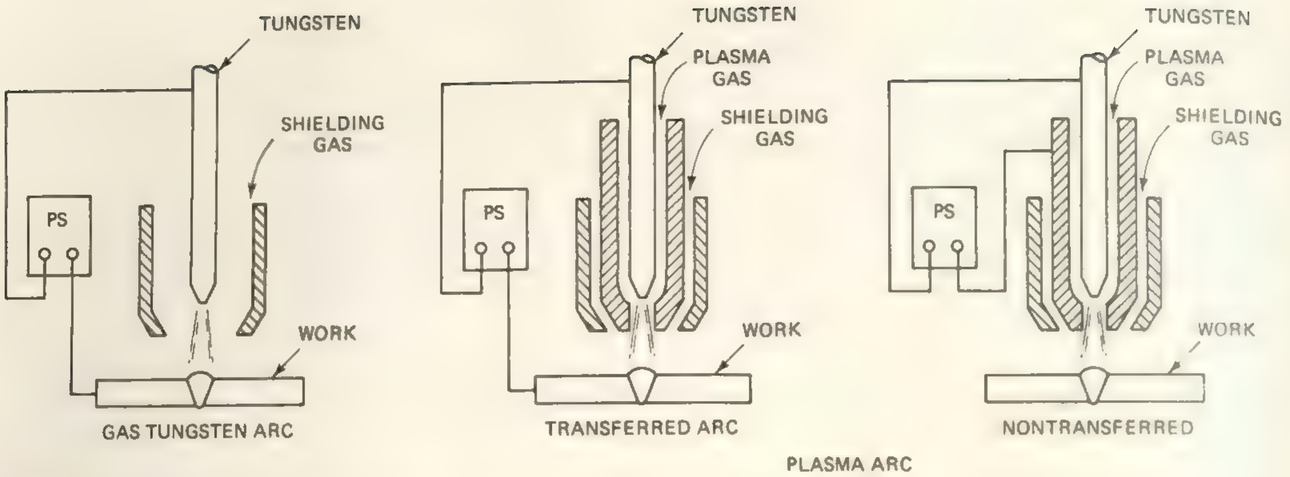


FIGURE 5-31 Modes of operation (GTAW and PAW).

of the plasma or constricted arc and the high-velocity plasma jet provide an increased heat transfer rate over gas tungsten arc welding when using the same current. This results in faster welding speeds and deeper weld penetration. This method of operation is used for welding extremely thin material and for welding multipass groove welds and fillet welds. Another method of welding with plasma is known as "keyhole" welding. In this method the plasma jet penetrates through the work piece and forms a hole known as a *keyhole*. Surface tension forces the molten base metal to flow around the keyhole to form the weld. The keyhole method can be used only for joints where the plasma can pass through the joint. It is used for base metals $\frac{1}{16}$ in. (1.6 mm) to $\frac{1}{2}$ in. (12 mm) in thickness and is affected by the base metal composition and the welding gases. The keyhole method provides for full-penetration single-pass welding which may be applied either manually or automatically in all positions. Keyhole welds have been made in aluminum $\frac{3}{4}$ in. (19 mm) thick.

Advantages and Major Uses

Advantages of plasma arc welding when compared to gas tungsten arc welding stem from the fact that it has a higher energy concentration. Its higher temperature, its constricted cross-sectional area, and the velocity of the plasma jet create a higher heat content. The other advantage is based on the stiff columnar plasma which does not flare like the gas tungsten arc. These factors provide the following advantages:

1. The torch-to-work distance is less critical than for gas tungsten arc due to the columnar form of the plasma. This is important for manual operation since it gives the welder more freedom to observe and control the weld.
2. High temperature and high heat concentration of the plasma allow for the keyhole effect, which provides complete-penetration single-pass welding of many joints. In this operation, the heat-affected zone and the form of the weld are more desirable. The heat-affected zone is smaller than with gas tungsten arc, and the weld tends to have more parallel sides, which reduces angular distortion.
3. The higher heat concentration and the plasma jet allow for higher travel speeds. From the welder's point of view, the plasma arc is more stable and is not as easily deflected to the closest point of base metal. Greater variation in joint alignment is possible with plasma than with gas tungsten arc welding. Plasma weld has deeper penetration capabilities and produces a narrower weld. This means that the depth-to-width ratio is more advantageous.

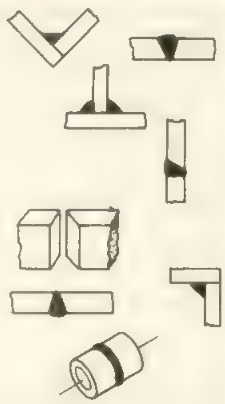
Some of the major uses of plasma arc are its application for the manufacture of tubing. Higher production rates based on faster travel speeds result from plasma over gas tungsten arc welding.

Plasma arc welding is also used for making small welds on instruments and small components made of thin metal. It is being used for making root-pass welds on pipe joints and is used for making butt joints of thin-wall tubing. The plasma arc welding process has also been used to do work similar to that done by electron beam welding in the open with much lower equipment cost.

Plasma arc welding is normally applied as a manual welding process, but it also used in automatic and machine applications. Figure 5-32 shows the normal methods of applying plasma arc welding. The plasma arc welding process is an all-position welding process (Figure 5-33).

Method of Applying	Rating
Manual (MA)	A
Semiautomatic (SA)	No
Machine (ME)	A
Automatic (AU)	A

FIGURE 5-32 Methods of applying (PAW).



Welding Position	Rating
1. Flat	A
Horizontal fillet	A
2. Horizontal	A
3. Vertical	A
4. Overhead	A
5. Pipe – fixed	A

FIGURE 5-33 Welding position capabilities (PAW).

Base Metal	Weldability
Aluminums	Weldable
Bronzes	Possible but not popular
Copper	Weldable
Copper nickel	Weldable
Cast, malleable, nodular	Possible but not popular
Wrought iron	Possible but not popular
Lead	Possible but not popular
Magnesium	Possible but not popular
Inconel	Weldable
Nickel	Weldable
Monel	Weldable
Precious metals	Weldable
Low carbon steel	Weldable
Low alloy steel	Weldable
High and medium carbon	Weldable
Alloys steel	Weldable
Stainless steel	Weldable
Tool steels	Weldable
Titanium	Weldable
Tungsten	Weldable

FIGURE 5-34 Metals weldable by the plasma arc process.

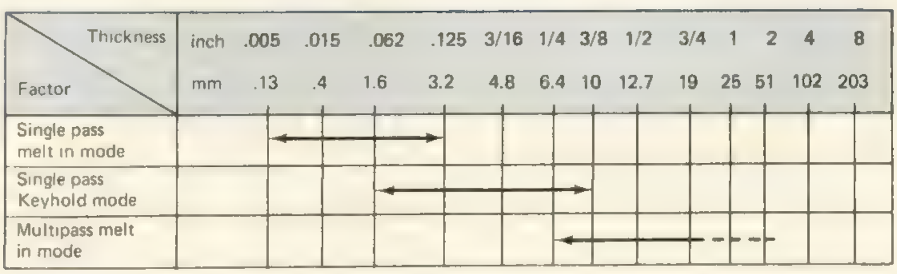


FIGURE 5-35 Base metal thickness range (PAW).

The plasma arc welding process is able to join practically all of the commercially available metals (Figure 5-34). The plasma arc welding process will join all the metals that the gas tungsten arc welding process will weld.

Regarding the range of thickness welded by the plasma process (Figure 5-35), consider first the keyhole mode of operation which can be used only where the plasma jet can penetrate the joint. In this mode the process can be used for welding material from ¹⁄₁₆ in. (1.6 mm) through ¾ in (19 mm). Thickness ranges vary somewhat with different metals. The melt in mode is used to weld material as thin as 0.002 in. (0.05 mm) up through ⅛ in.(3.2 mm). On the other hand, using multipass techniques, we can weld up to an unlimited thickness of metal. Note that filler rod is used for making welds in thicker material.

Joint Design

Joint design is based on the thicknesses of the metal to be welded and by the two modes of operation. For the keyhole mode, the joint design is restricted to full-penetration types. The preferred joint design is the square groove, with no minimum root opening. For root-pass

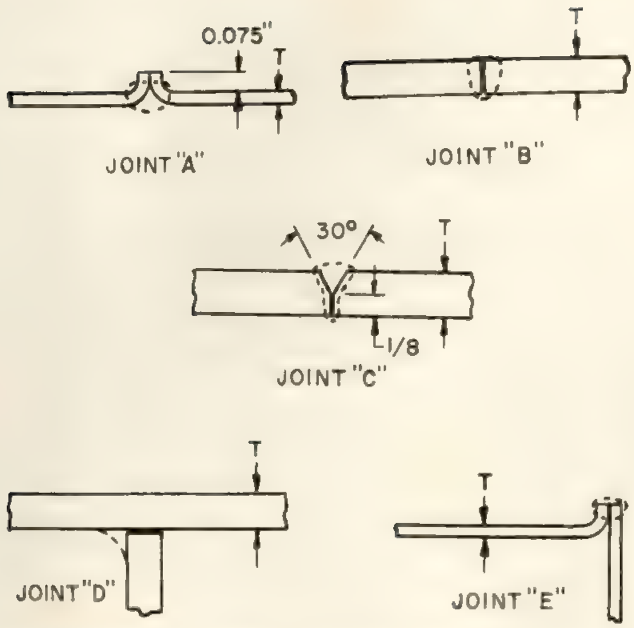


FIGURE 5-36 Joint designs for plasma arc.

work, on heavy-wall pipe, the U-groove design is used. The root face should be ⅛ in. (3.2 mm) to allow for full keyhole penetration.

For the melt-in method of operation for welding thin gauge, 0.020 in. (0.5 mm) to 0.100 in. (2.5 mm), metals the square groove weld should be utilized. For welding foil thickness, 0.005 in. (0.13 mm) to 0.020 in. (0.5 mm), the edge flange joint should be used. The flanges are melted to provide filler metal for making the weld.

When using the melt-in mode for thick materials the same general joint detail as used for shielded metal arc welding and gas tungsten arc welding can be employed. It can be used for fillets, flange welds, all types of groove welds, and so on. It can also be used for lap joints using arc spot welds and arc seam welds. Figure 5-36 shows various joint designs that can be welded by the plasma arc process.

Welding Circuit and Current

The welding circuit for plasma arc welding is somewhat more complex than for gas tungsten arc welding. An extra component is required. It is the control circuit necessary to aid in starting and stopping the plasma arc. The same power source is normally used. There are two gas systems, one to supply the plasma gas and the second for the shielding gas. The welding circuit for plasma arc welding is shown in Figure 5-37.

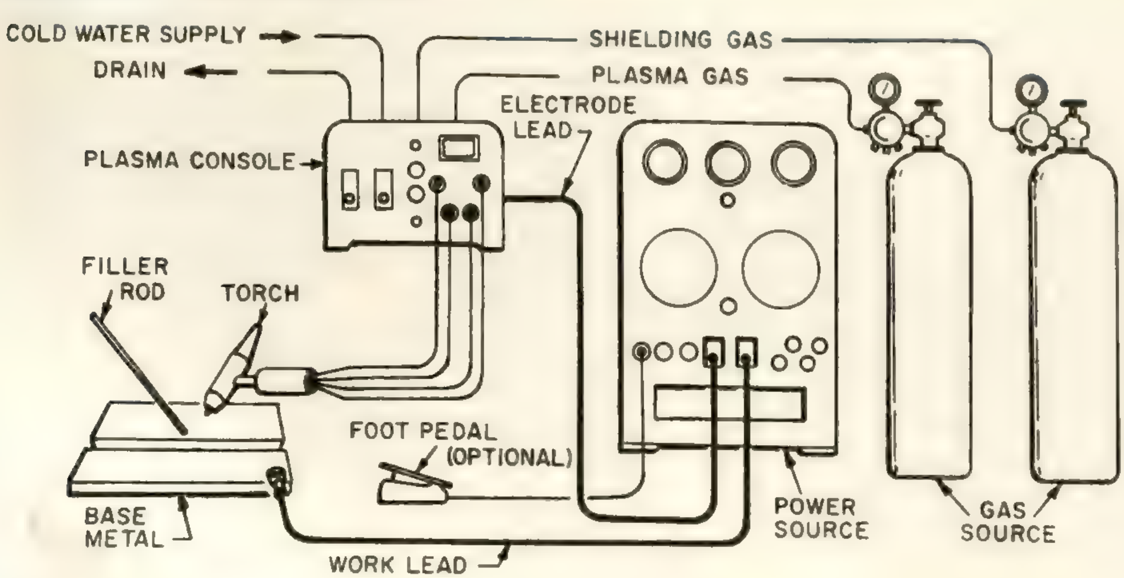
Direct current of a constant-current (CC) type is used. Alternating current is used for only a few applications.

Equipment Required to Operate

Power Source A constant-current drooping characteristic power source supplying the dc welding current is recommended; however, an ac/dc power source can be used. The power source should have an open-circuit voltage of 80 V and should have a duty cycle of 60%. It is very desirable to have a built-in contactor and provisions for remote control current adjustment. For welding very thin metals it should have a minimum amperage of 1 A. A maximum of 500 A is adequate for most plasma welding applications.

The *welding torch* for plasma arc welding is similar in appearance to a gas tungsten arc torch, but it is more

FIGURE 5-37 Circuit diagram (PAW).



complex. Figure 5-38 shows typical plasma torches. Plasma torches are water cooled, even the lowest-current range torch. This is because the arc is contained inside a chamber in the torch where it generates heat. If water flow is interrupted briefly the head assembly may melt. A cross section of a plasma arc torch head is shown in Figure 5-39. During the nontransferred period the arc will be struck between the orifice and the tungsten electrode. Manual plasma arc torches are made in various sizes, starting with 100 A up through 300 A. Automatic torches for machine operation of the same basic ratings are available. Cable assemblies come with the torches.

The torch utilizes the 2% thoriated *tungsten electrode.* Since the tungsten electrode is located inside the torch, it is almost impossible to contaminate it with base metal.

A **control circuit** is required for plasma arc welding. The plasma arc torches are designed to connect to the control console rather than to the power source. The control console includes a power source for the pilot arc, delay timing systems for transferring from the pilot arc to the transferred arc, and water and gas valves and separate flowmeters for the plasma gas and the shielding gas. Usually the console is connected to the power source and may operate the contactor. The control console will also contain a high-frequency arc starting unit, torch protection circuit, and an ammeter. The high-frequency is used to initiate the pilot arc. Torch protective devices include water and plasma gas pressure switches which interlock with the contactor. A **wire feeder** may be used for machine or automatic welding and must be the constant speed type. The wire feeder must have a speed adjustment covering the range from 10 in. (254 mm) per minute to 125 in. (3.18 m) per minute feed speed.

FIGURE 5-38 Typical manual plasma arc torch.

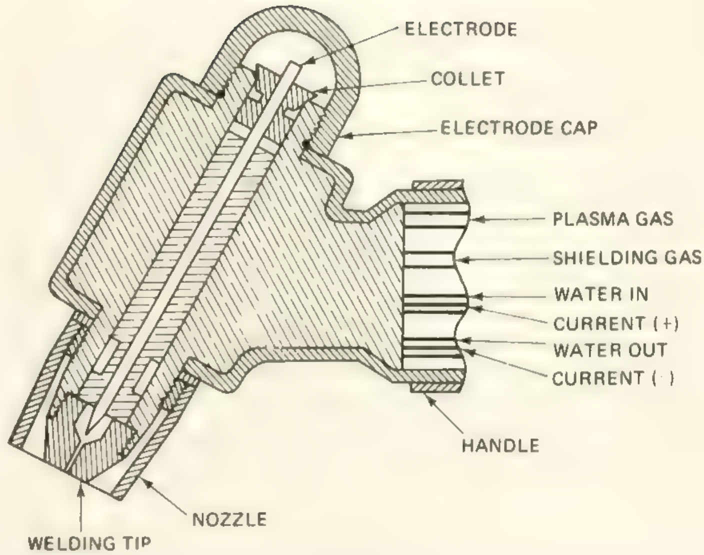


FIGURE 5-39 Cross section of plasma arc torch head.

Materials Used

Filler metal is normally used except when welding the thinnest metal. The composition of the filler metal should match that of the base metal. The size of the filler metal rod depends on the thickness of the base metal being welded and the welding current. The filler metal is usually added to the pool manually, but can be added automatically.

Plasma and Shielding Gas An inert gas, either argon, helium, or a mixture, is used for shielding the weld area from the atmosphere. Argon is more commonly used because it is heavier and provides better shielding at lower flow rates.

For flat and vertical welding, a shielding gas flow of 15 to 30 ft^3/hr (7 to 14 liters/min) is usually sufficient. Overhead position welding requires a slightly higher flow rate. Argon is usually used for the plasma gas at a flow rate of 1 ft^3/hr (0.5 liters/min) up to 5 ft^3/hr (2.4 liter/min) for welding, depending on torch size and the application. Active gases are not recommended for the plasma gas. In addition to the plasma and shielding gases, cooling water is required.

Quality, Deposition Rates, and Variables

The quality of the plasma arc welds are extremely high and usually higher than gas tungsten arc welds because there is little or no possibility of tungsten inclusions in the welds. The skill of the welder is a major factor with respect to the quality of welds. A welder will find the

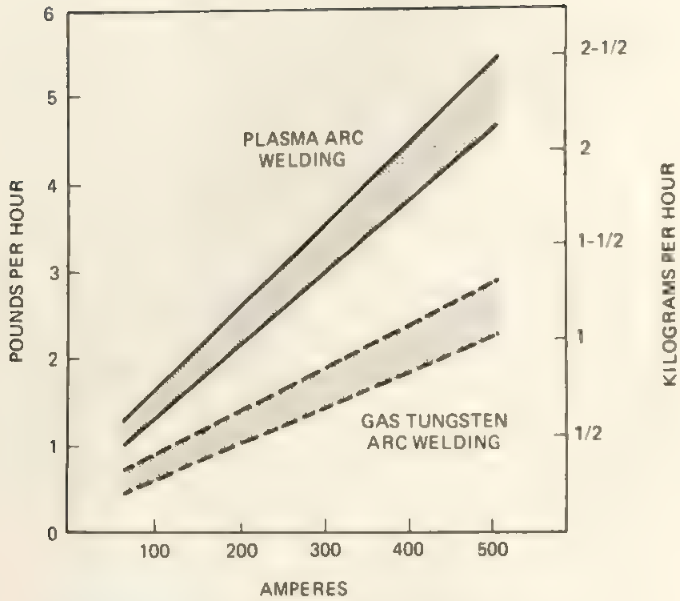


FIGURE 5-40 Deposition rates (PAW).

plasma arc welding process easier to use than the gas tungsten arc process which helps ensure weld quality.

Deposition rates for plasma arc welding are higher than for gas tungsten arc welding (Figure 5-40). Weld schedules for the plasma arc process are shown in Figure 5-41.

The process variables for plasma arc welding are shown in Figure 5-42. Most of the variables shown for plasma arc are similar to the other arc welding processes. There are two exceptions: the plasma gas flow and the orifice diameter in the nozzle. These are unique to plasma welding. The major variables exert considerable control in the process. The minor variables are generally fixed at optimum conditions for the given application. All variables should appear in the welding procedure. Variables such as the angle of the tungsten electrode, the setback of the electrode, and electrode type are considered fixed for the application. The plasma arc process does respond differently to these variables than does the gas tungsten arc process. The stand-off or torch-to-work distance is less sensitive with plasma, but the torch angle when welding parts of unequal thicknesses is more important than with gas tungsten arc.

Tips for Using the Process

The most important tip for using plasma arc welding is to properly maintain the welding torch. The tungsten electrode must be precisely centered and located with respect to the orifice in the nozzle. The pilot arc current must be kept sufficiently low, just high enough to maintain a stable pilot arc. When welding extremely thin materials in the foil range the pilot arc may be all that is necessary.

When filler metal is used, it is added in the same manner as gas tungsten arc welding. However, with the torch-to-work distance a little greater there is more freedom for adding filler metal. Equipment must be prop-

FIGURE 5-41 Weld procedure schedules for manual PAW.

Material	Material Thickness in.	Type of Weld	Orifice Dia. in.	Filler Dia. in.	Shield Gas at 20 CFH	Plasma Gas Flow CFH Argon	Weld Current - Amps	No. of Passes	Travel Speed ipm
Stainless steel (1)	0.008	Edge butt	0.093	–	A	0.5	12 DCEN	1	7
	0.008	Edge butt	0.093	–	A-5H_2	0.5	10 DCEN	1	13
	0.020	Square groove	0.046	–	A-5H_2	0.5	12 DCEN	1	21
	0.030	Square groove	0.046	–	A-5H_2	0.5	34 DCEN	1	17
	0.062	Square groove	0.081	–	A-5H_2	0.7	65 DCEN	1	14
	0.093	Square groove	0.081	–	A	2.0	85 DCEN	1	12
	0.093	Square groove	0.081	–	A-5H_2	2.0	85 DCEN	1	16
	0.125	Square groove	0.081	–	A	2.5	100 DCEN	1	10
	0.125	Square groove	0.081	–	A-5H_2	2.5	100 DCEN	1	16
	0.187	Square groove	0.081	–	A-5H_2	3.5	100 DCEN	1	7
	0.250	V-groove	0.081	–	A-5H_2	3.0	100 DCEN	First	5
	0.250	V-groove	0.081	3/32	A-5H_2	1.4	100 DCEN	Second	2
Mild steel	0.030	Square groove	0.081	–	A	0.5	45 DCEN	1	26
	0.080	Square groove	0.081	–	A	1.0	55 DCEN	1	17
Copper (1)	0.016	Edge butt	0.093	–	He	0.5	18 DCEN	1	24
Aluminum	0.036	Square groove	0.081	1/16	He	0.05	47 DCEP	1	24
	0.050	Edge joint	0.081	–	He	0.5	48 DCEP	1	22
	0.090	Fillet	0.081	3/32	He	1.4	34 DCEP	1	4

(1) Backing gas 5 to 10 CFH argon.

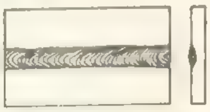
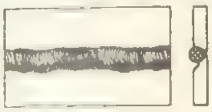
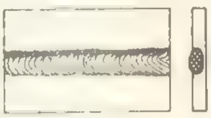
	SUNKEN BEAD, UNDERCUT TOO MUCH PENETRATION
	WELDING CURRENT IS TOO HIGH OR TRAVEL SPEED IS TOO SLOW
	BEAD TOO SMALL, IRREGULAR LITTLE PENETRATION
	WELDING CURRENT IS TOO LOW OR PLASMA GAS FLOW IS TOO LOW OR TRAVEL IS TOO FAST
	UNDERCUT AND IRREGULAR EDGES
	THE PLASMA GAS FLOW IS TOO HIGH
	PROPER SIZE BEAD EVEN RIPPLE AND GOOD PENETRATION
	CORRECT CURRENT, EVEN TORCH MOVEMENT, PROPER ARC VOLTAGE AND PLASMA GAS FLOW

FIGURE 5-42 Quality and common faults (PAW).

erly adjusted so that the shielding gas and plasma gas are in the right proportions. Proper gases must also be used. Plasma gas flow also has an important effect. The safety considerations for plasma arc welding are the same as for gas tungsten arc welding.

Limitations of the Process

The major limitations of the process have to do more with the equipment and apparatus. The torch is more delicate and complex than a gas tungsten arc torch. Even the lowest rated torches must be water cooled. The tip of the tungsten and the alignment of the orifice in the nozzle is extremely important and must be maintained within very close limits. The current level of the torch cannot be exceeded without damaging the tip. The water-cooling passages in the torch are relatively small and for this reason water filters and deionized water are recommended for the smaller torches. The control console adds another piece of equipment to the system which makes the system more expensive.

Variations of the Process

The welding current may be pulsed to gain the same advantages as pulsing provides for gas tungsten arc welding. A high current pulse is used for maximum penetration but is not on full time to allow for metal solidification. This gives a more easily controlled puddle for out-of-position work. Pulsing can be accomplished by the same control as is used for gas tungsten arc welding.

Programmed welding is also employed for plasma arc welding. The same power source with programming abilities is used and offers advantages for certain types of work. The complexity of the programming depends on the needs of the specific application. In addition to programming the welding current it is oftentimes necessary to program the plasma gas flow. This is particularly important when closing a keyhole, which is required to make the root pass of a weld joining two pieces of pipe.

The method of feeding the filler wire with plasma is essentially the same as for gas tungsten arc welding. The "hot wire" concept can be used. This means that low-voltage current is applied to the filler wire to preheat it prior to going into the weld puddle.

The low current (below 50 amps) has found many uses for precision welding of extremely thin pieces. Higher-current plasma welding applications for aluminum are using the variable polarity power source and making keyhole welds that have water-clear x-rays. Automatic applications are becoming more popular. The aircraft industries, jet engine industry, piping, tubing, and precision instrument industries are users of the plasma arc welding process.

5-4 CARBON ARC WELDING

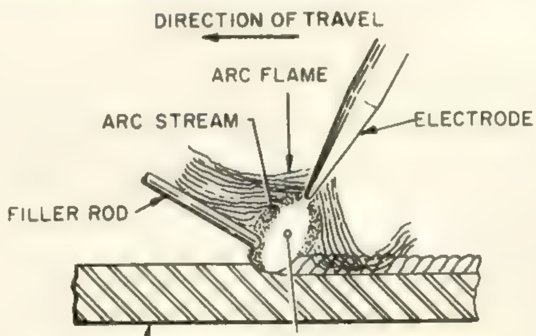
In the carbon arc welding (CAW) process, an arc is used between a carbon electrode and the weld pool. The process is used with or without shielding and without the application of pressure. Filler metal may or may not be used.

Principles of Operation

Carbon arc welding uses a single electrode with the arc between it and the base metal (Figure 5-43). It is the oldest arc welding process. It is included here for historical purposes. It is not popular today. There are two variations.

In carbon arc welding, the heat of the arc between the carbon electrode and the work melts the base metal and, when used, also melts a filler rod. As the molten

FIGURE 5-43 Process diagram (CAW).



metal solidifies a weld is produced. The carbon graphite electrode, considered to be nonconsumable, errodes away fairly rapidly and as it disintegrates produces a shielding atmosphere of carbon monoxide and carbon dioxide gas. These gases displace the atmosphere and prohibit the oxygen and nitrogen from coming into contact with the molten metal. Filler metal when employed is normally the same composition as the base metal. Bronze filler metal can be used for brazing and braze welding.

Advantages and Major Uses

The single electrode carbon arc welding process is no longer widely used. It is used for welding copper since it can be used at high currents to develop the high heat usually required. It is also used for making bronze repairs on cast iron parts. When welding thinner materials the process is used for making autogenous welds or welds without adding filler metal. Carbon arc welding is also used for joining galvanized steel. In this case the bronze filler rod is added by placing it between the arc and the base metal.

The carbon arc welding process is normally manually applied. In its early use it was mechanized. Electromagnetic coils were added around the electrode to direct the arc to the weld joint, and a rope-type material was fed into the arc which was consumed to create a protective arc atmosphere. This provided a machine welding system that had fairly high production capacities. This system is no longer of industrial significance. The normal method of applying is shown in Figure 5-44.

The manual carbon arc process is an all-position welding process. It is used as a heat source to generate the weld pool which can be carried in any position. Figure 5-45 shows the welding position capabilities.

Method of Applying	Rating
Manual (MA)	Most popular
Semiautomatic (SA)	Not used
Machine (ME)	Not popular
Automatic (AU)	Not popular

FIGURE 5-44 Methods of applying (CAW).

Weldable Metals

Mild and low-carbon steels are most widely welded with the carbon arc process, followed by copper. The carbon arc has been used for welding other nonferrous metals. The greatest use of the carbon arc is for brazing and to deposit wear-resistant surfaces. Various filler metals are used. The carbon arc is used for repairing iron castings. The filler metal can be cast iron or bronze.

Welding Position	Rating
1. Flat	A
Horizontal fillet	A
2. Horizontal	A
3. Vertical	A
4. Overhead	A
5. Pipe–fixed	-

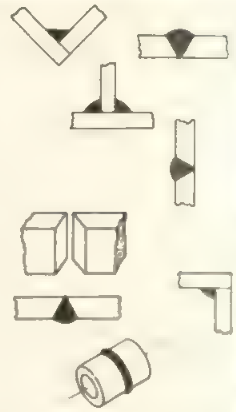


FIGURE 5-45 Welding position capabilities (CAW).

The carbon arc is used in repair of steel castings. In this case, the carbon arc is used primarily as a puddling method for filling casting defects or holes. The high-current capacity is utilized to heat the defective area to a molten stage and feed in filler metal that matches the composition of the casting. The base metal thickness range and the joint design used are very similar to those of shielded metal arc welding.

Welding Circuit and Current

The welding circuit for carbon arc welding is the same as for shielded metal arc welding. The power source is the conventional or constant current type with drooping volt-ampere characteristics.Normally, a 60% duty cycle power source is utilized. The power source should have a voltage rating of 50 V since this voltage is used when welding copper with the carbon arc.

Carbon Arc Welding Electrode Holders

Electrode holders for carbon arc welding are different than those for shielded metal arc welding. The single carbon electrode holder (Figure 5-46) comes in four sizes based on the welding current capacity, which relates to the carbon electrode size. These electrode holders are not insulated, and the carbon is usually gripped by collet action or by a setscrew.

Single-electrode carbon arc welding is always used with direct-current electrode negative DCEN (straight polarity). In the carbon-to-steel arc the positive pole (anode) is the pole of maximum heat. If the electrode were positive, the carbon electrode would erode very rapidly because of the higher heat, and would cause black carbon smoke and excess carbon which could be absorbed

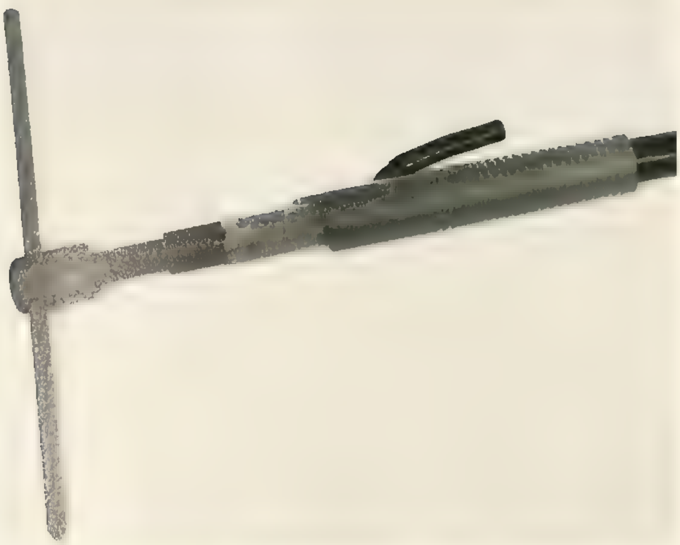


FIGURE 5-46 Carbon arc single electrode holder.

by the weld metal. Alternating current is not recommended for single-electrode carbon arc welding. The electrode should be adjusted often to compensate for the erosion of the carbon. From 3 to 5 in. of the carbon electrode should protrude through the holder toward the arc.

Carbon Electrode

There are two types of electrodes used for carbon arc welding. One is made of pure graphite and the other of baked carbon. The pure graphite electrode does not erode away as quickly as the carbon electrode. It is more expensive and more fragile. Electrodes are available in diameters ranging from 5/32 in. (4 mm) through 3/4 in. (19 mm) in diameter with a length of either 12 or 17 in. (310 or 460 mm).[10]

Welding Schedules

The welding schedule for carbon arc welding galvanized iron using silicon bronze filler metal is given in Figure 5-47. A short arc must be used to avoid damaging the galvanizing. The arc must be directed on the filler wire, which will melt and flow onto the joint.

For welding copper use a high arc voltage and follow the schedule given in Figure 5-48. Figure 5-49 shows the welding current to be used for each size of the two types of carbon electrodes.

Twin Carbon Arc Welding

Twin carbon arc welding (CAW-T) is a carbon arc welding process variation that produces coalescence of metals by heating them with an electric arc between two carbon electrodes. No shielding is used. Pressure and filler metals may or may not be used. The twin carbon arc can also be used for brazing.

The electrode holder (Figure 5-50) is used for twin electrodes. It comes in only one size but will accommodate several sizes of electrodes. It is not insulated.

The twin carbon electrode holder is designed so that one electrode is moveable and can be touched against the other to initiate the arc. The carbon electrodes are held in the holder by means of setscrews and are adjusted so that they protrude equally from the clamping jaws. When the two carbon electrodes are brought together, the arc is struck and established between them. The angle of the electrodes provides an arc that forms in front of the apex angle and fans out as a soft source of concentrated heat or arc flame. It is softer than that of the single carbon arc. The temperature of this arc flame is between 8000 and 9000°F (4426° and 4982°C).

Alternating current is used for the twin carbon welding arc. With alternating current the electrodes will burn off or disintegrate at equal rates. Direct-current power can be used, but when it is, the electrode connected to the positive terminal should be one size larger than the electrode connected to the negative terminal. This will ensure an even burning of the carbon electrodes since the positive electrode disintegrates at the higher rate. The arc gap or spacing between the two electrodes is adjustable during welding and must be adjusted more or less continuously to provide the fan-shaped arc.

The twin carbon arc is a very useful source of heat that can be used for many applications in addition to

FIGURE 5-47 Welding procedure schedule: galvanized steel.

Material Thickness			Electrode Size		Filler Rod Size		Welding Current	Arc Voltage
Gage	in.	mm	in.	mm	in.	mm	amps DC	Electrode Neg.
24	0.024	0.6	3/16	5	3/32	2.4	25-30	13-15
22	0.020	0.7	3/16	5	3/32	2.4	25-30	13-15
20	0.036	0.9	3/16	5	3/32	2.4	30-35	14-16
18	0.048	1.2	1/4	6.4	1/8	3.2	30-35	14-16
16	0.060	1.5	1/4	6.4	1/8	3.2	30-35	14-16
14	0.075	1.9	1/4	6.4	1/8	3.2	30-35	14-16
12	0.105	2.7	1/4	6.4	1/8	3.2	35-40	15-17

Thickness of Copper			Diameter of Electrode and Filler Rod					
Decimal Inches	Fraction Inches on US Gage in.	mm	Electrode Carbon in.	Electrode Carbon mm	Filler Rod in.	Filler Rod mm	Welding Current DC Amps	Voltage Electrode Negative
0.05	18		3/16	4.8	3/32		80	
0.0563	17				3/32	2.4	90	35
0.0625	1/16	1.6	3/16	4.8	1/8		90	
0.07	15				1/8	3.2	100	40
0.078	5/64	1.9	1/4	6.4	5/32		120	
0.094	3/32	2.4			5/32		135	
0.109	7/64	2.8			5/32	11.9	140	40
0.125	1/8	3.2	1/4	6.4	3/16		150	
0.141	9/64	3.6			3/16		160	
0.156	5/32	3.9			3/16		165	
0.172	11/64	4.4			3/16		170	
0.1875	3/16	4.8			3/16	4.8	185	45
0.203	13/64	5.2	5/16	7.9	1/4		200	
0.219	7/32	5.6			1/4		200	
0.234	15/64	5.9			1/4		205	
0.25	1/4	6.4			1/4		215	
0.266	17/64	6.7			1/4	6.4	225	45
0.281	9/32	7.1	5/16	7.9	5/16		250	
0.3125	5/16	7.9			5/16		250	
0.344	11/32	8.7			5/16		255	
0.375	3/8	9.5			5/16		270	
0.406	13/32	10.3			5/16	7.9	290	50
0.4375	7/16	11.1	3/8	9.5	3/8		300	
0.4688	15/32	11.9			3/8		310	
0.5	1/2	12.7			3/8	9.5	325	50

FIGURE 5-48 Welding procedure schedule: copper.

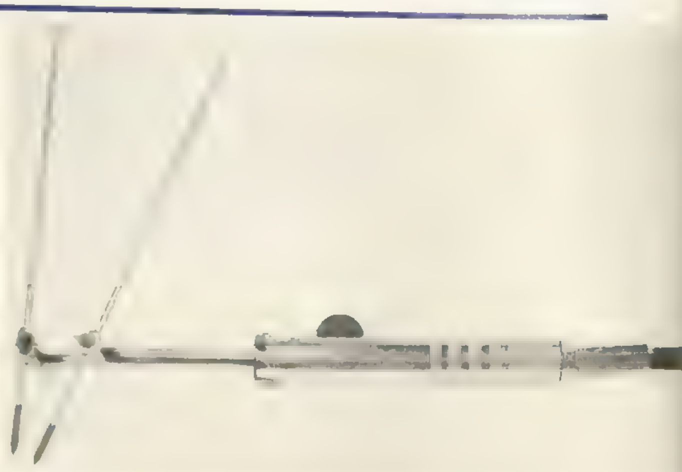
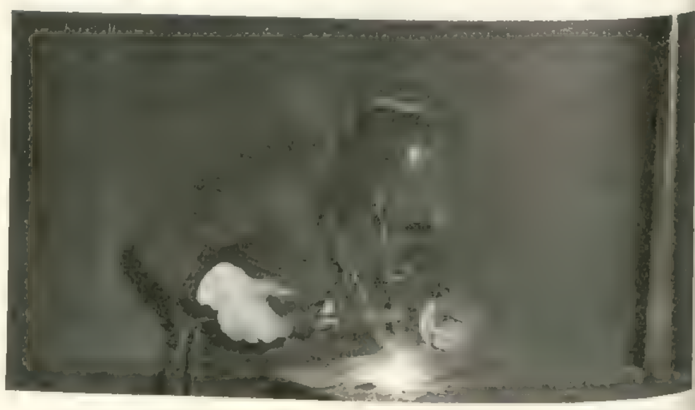


FIGURE 5-50 Twin carbon electrode holder.

FIGURE 5-49 Welding current for carbon electrode types.

Electrode Diameter in.	Electrode Diameter mm	Carbon Electrodes DCEN Amps	Graphite Electrodes DCEN Amps
1/8	3.2	15-30	15-35
3/16	4.8	25-55	25-60
1/4	6.4	50-85	50-90
5/16	7.9	75-115	80-125
3/8	9.5	100-165	110-165
7/16	11.1	125-185	140-210
1/2	12.7	150-225	170-260
5/8	15.9	200-310	230-370
3/4	19.0	250-400	290-490
7/8	22.2	300-500	400-750



Carbon Electrode Diameter in.	mm	Welding Current Amperes AC	Arc Voltage	Base Metal Thickness in.	mm
1/4	6.4	55	35-40	1/16	1.6
5/16	7.9	75	35-40	1/8	3.2
3/8	9.5	95	35-40	1/4	6.4
3/8	9.5	120	35-40	over 1/4	over 6.4

FIGURE 5-51 Welding current for carbon electrodes (twin torch).

welding, brazing, and soldering. It can be used as a heat source to bend or form metal. The welding current settings or schedules for different sizes of electrodes are shown in Figure 5-51.

The twin carbon electrode method is used by the hobbyist and for maintenance work in the home, in the small shop, and on the farm. It is used with the low-duty cycle single-phase limited-input ac transformer welding machines. It can be used in any position and on any materials where the heat is required. It is relatively slow and for this reason does not have too much use as an industrial welding process.

5-5 STUD ARC WELDING

Stud arc welding is "an arc welding process that uses an arc between a metal stud or similar part and the workpiece. The process is used with or without shielding gas or flux, with or without partial sheeting from ceramic ferrules surrounding the stud, with the application of pressure after the faying surfaces are sufficiently heated, and without filler metal. Partial shielding may be obtained by the use of a ceramic ferrule surrounding the stud, and shielding gas or flux may or may not be used."

Principles of Operation

There are four variations of stud welding. Stud arc welding, also called drawn arc stud welding, is the most popular and will be described; however, the other methods—capacitor discharge stud welding, the drawn arc capacitor discharge stud welding, and the consumable ferrule type stud welding—will be discussed under "Variations of the Process" later in this section.

It is questionable if stud welding is a true arc welding process. It has a very specialized field of application and is not a metal joining process in the same manner as the others previously discussed. It end welds prepared studs to the base metal. The process is a combination of arc welding and forge welding. It is based on two steps. First, electrical contact between the stud and the base metal occurs and an arc is established. The heat of the arc melts the surface of the end of the stud and the work surface. As soon as the entire cross section of the stud and an area of equal size on the base metal are melted, the stud is forced against the base metal. The molten end of the stud joins with the molten pool on the work surface and as the metal solidifies the weld is produced. Partial shielding is accomplished by means of a ceramic ferrule that surrounds the arc area and by fluxing ingredients sometimes placed on the arcing end of the stud.

The making of a stud weld is shown in Figure 5-52. The stud gun (step A) holds the stud in contact with the workpiece until the welder depresses the gun trigger switch. This causes welding current to flow from the power source through the stud (which acts as an electrode) to the work surface. The welding current flow actuates a solenoid within the stud gun which draws the stud away from the work surface (step B) and establishes the arc. The arc time duration is controlled by a timer in the control unit. At the appropriate time the welding current is shut off, the gun solenoid releases its pull on the stud, and the spring loaded action plunges the stud into the molten pool of the workpiece (step C). The molten metal solidifies and produces the weld, plus a small reinforcing fillet. After solidification the gun is released from the stud and the ceramic ferrule is broken off revealing the weld (step D).

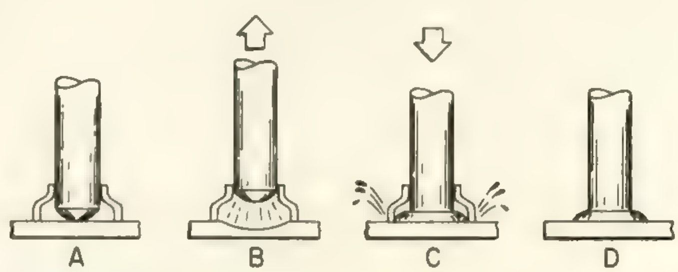


FIGURE 5-52 Stud welding process.

Advantages and Method of Application

The stud arc welding process is unique and is a special application process. It offers tremendous cost savings when compared to drilling and tapping for studs, or to manually welding studs to base metal. Stud welding does not destroy the water tightness or weaken the base metal in the way that drilled and tapped holes do.

Semiautomatic method of applying is the most com-

Method of Applying	Rating
Manual (MA)	No
Semiautomatic (SA)	A
Machine (ME)	B
Automatic (AU)	B

FIGURE 5-53 Method of applying (SW).

Welding Position	Rating
1. Flat	A
Horizontal fillet	–
2. Horizontal	A
3. Vertical	A
4. Overhead	B
5. Pipe—fixed	–

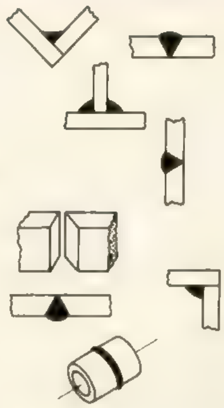


FIGURE 5-54 Welding position capabilities (SW).

mon for construction work and for ship work. Automatic feed and automatic location are becoming increasingly popular in the mass production and metalworking manufacturing companies. Robots are being used by the automobile industry. The various methods of applying are listed in Figure 5-53.

This process is practically an all-position process (Figure 5-54); however, the overhead position is difficult.

This process is used most widely for welding studs to mild steels, low-alloy steels, and some of the austenitic stainless steels. Some of the process variations can be used on nonferrous metals. Figure 5-55 shows the base metals that can be welded. The stud should have the same analysis as the base metal.

The minimum recommended plate thickness to permit efficient welding without burn-through or excessive distortion is shown in Figure 5-56. As a general rule, the minimum thickness of the plate or base metal is 20% of the stud base diameter. To develop full strength of the stud, the plate thickness should be not less than 50% of the stud base diameter.

Joint Design

Stud welding is a special application process. The joint would be considered a T type. The weld would be a square groove type with a small reinforcing fillet all around. A variety of studs is shown in Figure 5-57.

Welding Circuit and Equipment Required to Operate

Figure 5-58 is the circuit diagram for stud welding. It shows the welding power source, the stud gun, and the special control unit.

Direct current is preferred for stud arc welding, and the stud gun (electrode) is connected to the negative terminal (DCEN) or straight polarity. The workpiece is attached to the positive pole. Ac is not recommended for stud arc welding, and direct-current constant voltage is usable but not recommended.

The *power source* for stud welding is normally a direct-current motor generator or rectifier constant-current welding machine. The size of the welding machine is based on the size of the stud to be welded (Figure 5-59). Welding machines can be paralleled to provide sufficient current. Stud welding has a short arc period, rarely lasting over 1 second. Therefore, overcapacity currents are drawn from the machine for a shorter period than the normal duty cycle requirements of a machine. For this reason, the welding machine must have sufficient overload

FIGURE 5-55 Metals weldable (SW variations).

		STUD WELDING VARIATIONS		
Base Metal	Conventional Arc Stud	Contact Capacitor Discharge	Drawn Arc Capacitor Discharge	Fusible Cartridge
Aluminum	No	Weldable	Weldable	No
Brass—bronze	No	Weldable	Weldable	No
Copper	No	Weldable	Weldable	No
Low carbon steel	Weldable	Weldable	Weldable	Weldable
Low alloy steel	Weldable	Weldable	Weldable	Weldable
Medium carbon	Limited	Weldable	Weldable	Weldable
Stainless steel	Weldable	Weldable	Weldable	Weldable
Zinc	No	Weldable	Weldable	No
Dissimilar metals	Limited	Weldable	Weldable	No

Stud Base Diameter			Base Metal Thickness		
fraction	inch	mm	inch	gage	mm
3/16	0.187	4.7	0.059	16	1.5
1/4	0.250	6.3	0.075	14	1.9
5/16	0.312	7.9	0.104	12	2.6
3/8	0.375	9.5	0.117	11	2.9
7/16	0.437	11.1	0.135	10	3.4
1/2	0.500	12.7	0.164	–	4.1
5/8	0.625	15.8	0.209	–	5.3
3/4	0.750	19.0	0.250	1/4"	6.3
7/8	0.875	22.2	0.312	5/16"	7.9
1	1.000	25.4	0.375	3/8"	9.5

FIGURE 5-56 Minimum recommended base metal thickness (steel) (SW).

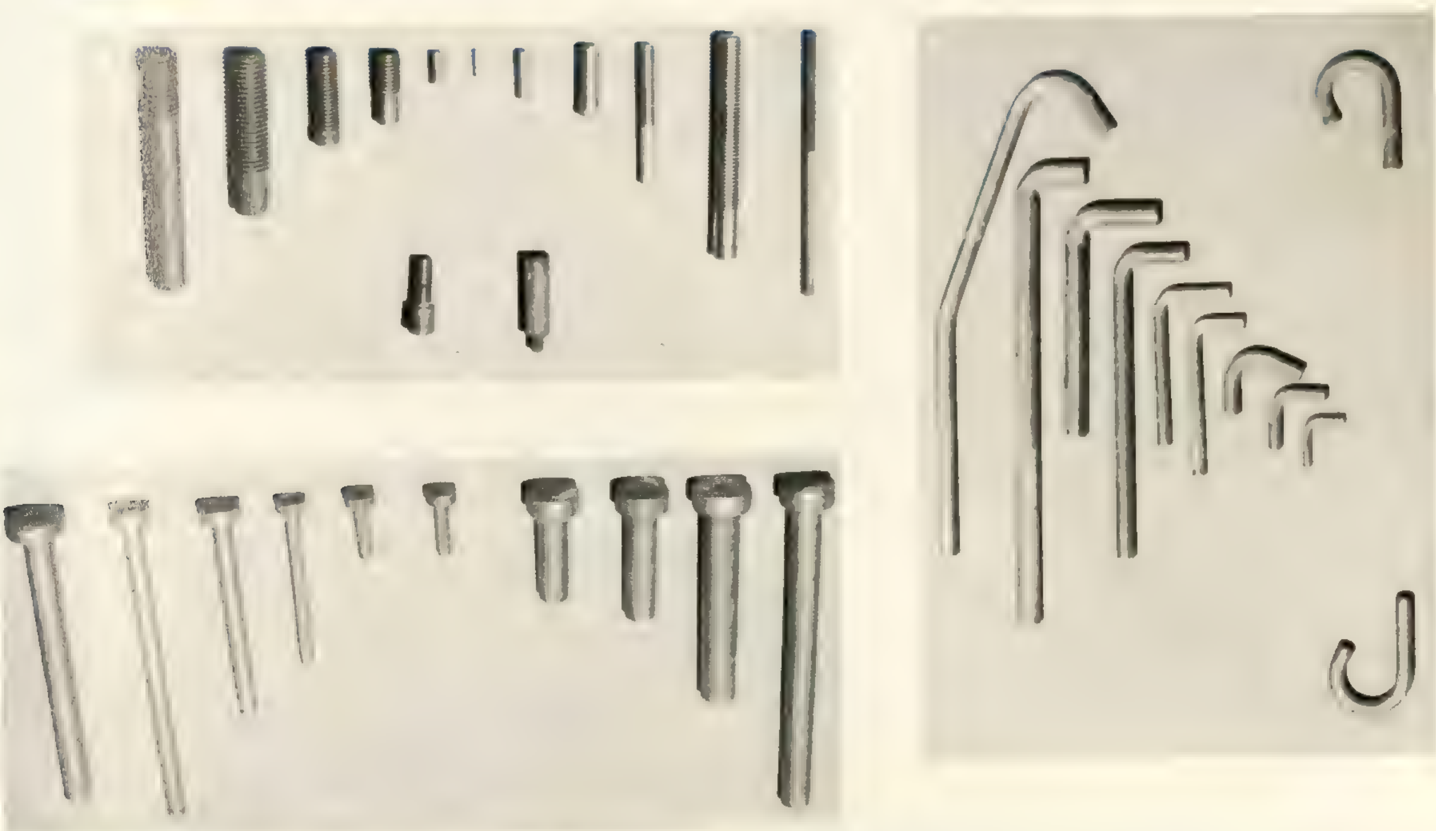


FIGURE 5-57 Variety of studs available.

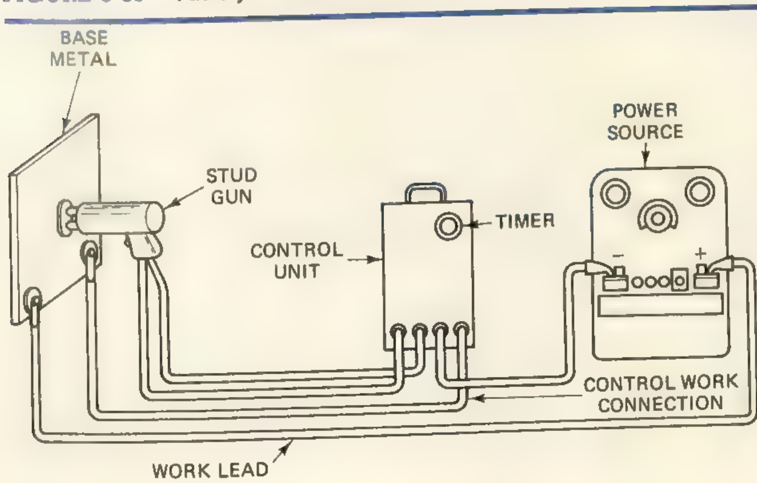


FIGURE 5-58 Circuit diagram (SW).

Stud inch	Diameter mm	Amperes Required	Weld Cable		Power Source		Alternate Power Source	
			Size	No. Reqd.	No.	Rated Size	No.	Rated Size
3/16	4.76	300	2/0	1	1	300 Amp		
1/4	6.35	400	2/0	1	1	400 Amp		
5/16	7.94	500	2/0	1	1	400 Amp		
3/8	9.53	600	2/0	1	1	600 Amp	2	300 Amp
7/16	11.11	700	2/0	1	1	600 Amp	2	300 Amp
1/2	12.70	900	4/0	1	1	1000 Amp	2	400 Amp
5/8	15.87	1150	4/0	1	1	1000 Amp	2	600 Amp
3/4	19.05	1600	4/0	2	2	1000 Amp	2	600 Amp
7/8	22.23	1800	4/0	2	2	1000 Amp		
1	25.40	2000	4/0	2	2	1000 Amp		

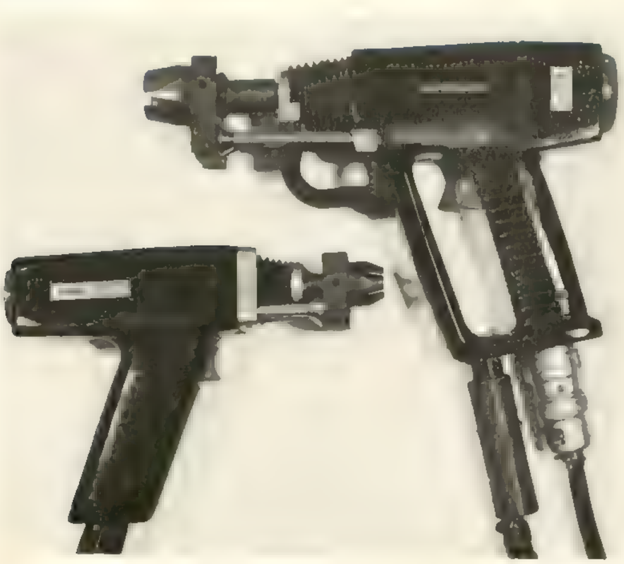
Note generator welders have greater overload capacity than rectifiers.

FIGURE 5-59 Power source requirements for different sizes of studs.

capacity. It is important to check the specifications of the welding power source to determine that it can be used for stud welding. See Figure 5-59 for the recommended welding power sources and cable for welding different sizes of studs. Generator welding machines have higher overload capacities because of the flywheel effect.

The *stud welding gun* is designed specifically and only for stud welding. The gun resembles a pistol with a trigger switch for starting the weld cycle. Two different stud guns are shown in Figure 5-60. The gun contains the solenoid lifting mechanism as well as the spring for plunging the stud into the molten weld pool. The welding current must flow through the gun itself. The gun must also contain adjustments to establish the arc length and to provide for accurate plunge dimensions. The gun is equipped with a stand-off device, to hold it in proper relationship to the work. In addition, the gun allows the use of different types of collets or chucks for each size and type of stud. The stand-off device or arc shield holder must be adjustable to accommodate different types of chucks. Guns are available in different sizes based on the size of the studs and the welding current involved.

FIGURE 5-60 Stud guns.



The *weld timer controller* is a separate unit to establish the arc time required for proper heating. The control unit also contains a contactor capable of breaking the welding current at the end of the arcing period. The timer is calibrated in electrical cycles which are defined as 1/60 of a second, for 60 Hz power. Control units for stud welding are designed specifically to interconnect with the welding stud gun and the power source. Stud guns of one manufacturer should not be used with control panels or studs of another manufacturer. The control cable is between the stud gun and the timer only.

Materials Used

Electrode and filler metal are combined in the stud. Studs are made in many sizes and shapes. Normally, studs are made of low-carbon steel having a minimum yield strength of 45,000 psi (20,400 kg) and a 20% minimum elongation in 2 in. (50 mm). Stud types can be threaded fasteners, internally threaded fasteners, flat fasteners with rectangular cross sections, header pins, eye bolts, slotted pins, keys, and so on. Studs are also made of different metals. The stud gun manufacturers and stud manufacturers offer catalogs with engineering data pertaining to the exact design of the studs they manufacture. Studs up to 1 in. (25 mm) diameter can be welded. The round stud is the most common. Square and rectangular shaped studs are available. Most studs include a method of fluxing. This is accomplished differently. In some cases, granular flux is enclosed in the end of the stud by means of a thin metal retaining shield. Other makes utilize a solid flux inset in the end of the stud, while others have a coating of flux covering the arcing end of the stud. Flux acts as an arc stabilizer and helps protect the molten metal from the atmosphere during welding.

A short portion of the stud is melted off during the arcing period so that the finished length is less than the original length of the stud. The amount of burn-off material depends on the diameter of the stud and somewhat on the application. The burn-off value for small studs is 1/8 in. (3.2 mm), 5/32 in. (4 mm) for medium-size studs, and 3/16 in. (4.8 mm) for the larger studs.

A ceramic *ferrule* must be used for each stud. This is sometimes called an *arc shield*. This ferrule is placed over the stud and held in position by a holder or grip on the gun. The ceramic ferrule performs the following functions.

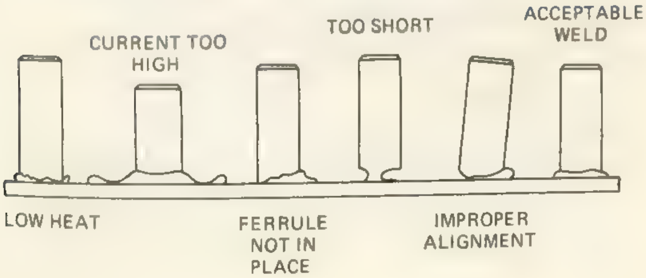
1. Concentrates the heat of the arc in the weld area
2. Reduces oxidation of the molten metal during welding by restricting contact with the atmosphere
3. Confines the molten metal
4. Eliminates the need for a welding headshield or helmet by shielding the arc from the welder

The inner surface shape of the ferrule is the same shape as the stud being used, usually cylindrical. It has a serrated shape at the base to form vents for escaping shielding gas. Internally it is shaped to help mold the molten metal around the base of the stud to form a small fillet. Specially designed ferrules may be obtained for specific applications. The ferrule is broken off the weld at the completion of the weld and discarded. It can be used only once.

Quality of Welds

The weld quality of properly made stud welds is excellent and usually exceeds the strength of the stud. Properly made welds depend on the weld schedule, the size of the power source, the gun chuck and hold down, the use of correct size of cables, and a good work connection. The work surface to be welded must be clean of paint, rust, heavy metal scale, and so on. It is necessary to hold the gun in the proper position and steady during the weld cycle. Figure 5-61 shows potential quality problems that can occur. Inspection of welds may be made both visually and mechanically. The normal visual inspection is to determine if a uniform fillet is produced completely around the periphery of the stud at its junction to the workpiece.

FIGURE 5-61 Potential quality problems.



Mechanical tests may be made by shearing the stud from the work or by pulling it from the work. The AWS Structural Code and Navy welding codes specify how these tests are to be made.[11]

Weld Schedules

The welding conditions for stud welding are given in Figure 5-62. This includes all factors necessary to set up procedures for stud welding.

Stud Dia. inches	Amps DCEP	Welding Volts	Time* Cycle	Lift (in.)	Plunge (in.)
3/16	300	30	7	1/16	1/8
1/4	400	30	10	1/16	1/8
5/16	500	30	15	1/16	1/8
3/8	600	28	20	1/16	1/8
7/16	700	28	25	1/16	1/8
1/2	900	28	30	3/32	5/32
5/8	1150	28	40	3/32	5/32
3/4	1600	26	50	1/8	3/16
7/8	1800	24	60	1/8	3/16
1	2000	24	70	1/8	3/16

*Based on 60 Hertz.

FIGURE 5-62 Stud arc welding conditions.

Welding Variables and Tips for Using

Stud welding is a relatively simple and foolproof welding process. The apparatus must be properly set up and adjusted for the size and type of studs to be welded. The settings and control schedules must be in agreement with the schedules based on stud sizes. Further, the stud gun must be equipped with the proper size holding devices.

Stud welding does not require manipulative skill necessary for the other arc welding processes. The most popular method of applying is semiautomatic where the welder holds the stud gun during the welding operation. The gun should be held by both hands, one hand in the same manner as gripping a pistol. and the other hand against the back of the gun to provide stability. It is necessary to place the stud tip against the base metal and push the gun toward the base metal to seat the ferrule firmly. This actually compresses the mechanism inside the gun for proper operation. When the trigger is pressed, the entire weld cycle is automatic, based on the settings of the control unit. The gun should not be moved during the welding operation. The arc will be noticed, and plunging action will be heard at the completion of the welding cycle. After the plunging operation, the gun should be

held steady for at least a half-second before withdrawing it from the welding stud.

There are a variety of problems that might occur in making a stud weld. If the current is too low a full-strength weld will not result. If it is too high there will be too much metal discharged from the weld. The time cycle must be set correctly. If the plunge is too short a full weld will not result. If the ferrule is not in place properly the weld will be offside. If the gun is not perpendicular to the work, the stud will be welded at an angle not perpendicular. Other problems can result if there is too much dirt, paint, or foreign material on the workpiece. Another problem may result if welding leads from the power source to the work and to the stud gun or control are not tight. There is also a problem if these cables are longer than recommended.

Every time a new job is started or a new setup is made, the welding procedure should be verified. This is done by bending a stud with hammer blows to see that the weld procedure produces a quality weld.

Safety Considerations

The ceramic ferrule or arc shield shields the arc from the welder and eliminates the need for the normal welding hood. The welder should wear safety glasses or flash goggles with a tinted shade. For overhead and vertical position welding above the welder's head, protective clothing is required. Gloves are recommended for all arc stud welding.

Limitations of the Process

The arc stud process is limited primarily to the mild and low-alloy steels. High-carbon and high-alloy steels should not be stud welded unless a heat-treating operation is performed. Stud welding can be performed on the austenitic types of stainless steels only. It cannot be used to weld nonferrous metals.

Variations of the Process

There are three variations of stud welding. These are:

1. The capacitor discharge stud welding method
2. The drawn arc capacitor discharge stud welding method
3. The fusible cartridge stud welding method

In the contact capacitor discharge stud welding variation, the energy for making the weld is stored at a low voltage in high-capacity capacitors. This method is called the stored energy system or percussive stud welding. The stud is slightly different since it has a small tip on the end of the stud. In operation this small tip is brought into contact with the base material and then pressure is

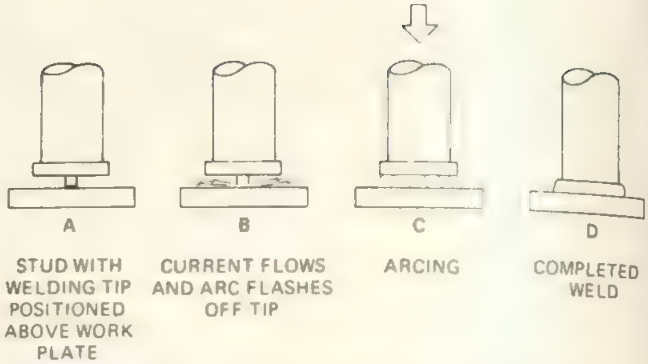
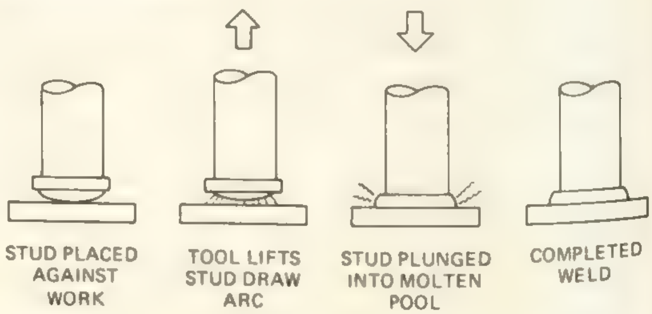


FIGURE 5-63 Sequence of operations: contact capacitor discharge.

applied by means of a spring or air pressure in the gun. The contactor then closes and the weld circuit is completed. The stored energy is discharged through the small tip or projection at the base of the stud, and it presents a high resistance to the electrical energy and rapidly disintegrates. This creates an arc which heats the surface of the stud and base metal. During this arcing period the stud is plunged to the base metal by means of a spring or air pressure. The weld is completed immediately following the high-intensity arc, in a short period of about 0.006 seconds. It is done so quickly that the heat effect on the parts is minimal. Figure 5-63 shows the sequence of operations. For welding mild steel neither flux nor shielding of any kind is used. However, only smaller studs are welded with this method, usually ¼ in. (6.4 mm) maximum diameter. The power source, stud gun, and controller are designed especially for this stud welding variation.

In the drawn-arc capacitor discharge stud welding variation, arc initiation is obtained in the same manner as arc stud welding. The sequence shown in Figure 5-64 is as follows. The stud is placed against the work, then it lifts from the work to draw an arc. Studs up to ¼ in. (6.4 mm) diameter are used. The arc time varies from 6 to 15 milliseconds, and then the stud is plunged into the molten pool and the weld is completed. Flux is not re-

FIGURE 5-64 Sequence of operations: drawn arc capacitor discharge.



quired but shielding gas may be used for welding such metals as aluminum. A special gun, control, and power source are required for this variation of stud welding. This method including power source and associated equipment is very similar to that used for contact capacitor discharge stud welding.

The fusible cartridge stud welding variation of stud welding is used in Europe.[12] The stud is square on the welding end without any special preparation. It ranges in diameter from 3/16 in. (5 mm) to 5/8 in. (16 mm). A fusiable cartridge which looks similar to an arc shield is placed on the end of the stud. The fusible cartridge, or ferrule, (Figure 5-65), is made of material similar to coating on an iron-powered electrode. The sequence of operations is shown in Figure 5-66. The arc is initiated by the flow of current through the fusible cartridge. Soon after initiation, full arcing across the face of the stud occurs. The weld cycle is controlled by the cartridge and as it disintegrates the stud is forced against the work piece by the spring in the gun. The end of the stud and the work piece are molten and when the molten metal solidifies the weld is complete. The weld cycle time is from ½ to 2½ seconds. The process is used for carbon steel and stainless steel. A fusible cartridge is used for each weld. The gun is special for this process variation. The power source is a conventional CC type. Either ac or dc can be used. A contactor is required, as well as a special control citcuit.

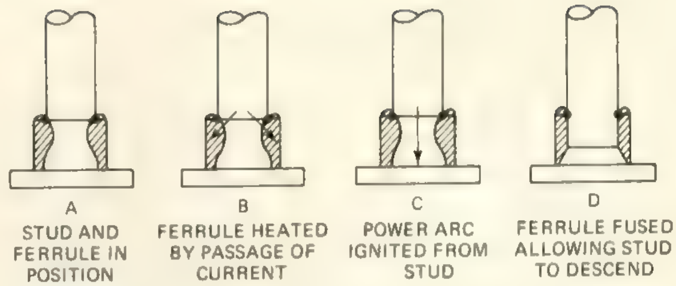
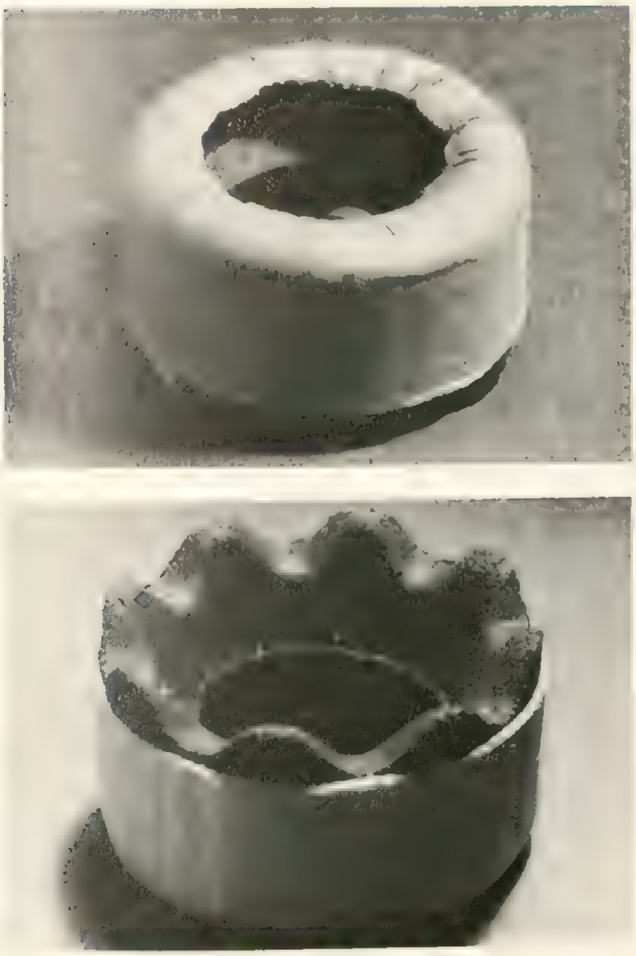


FIGURE 5-66 Sequence of operation: fusible cartridge.

FIGURE 5-65 Fusible cartridge.



Industrial Use and Typical Applications

The construction industry is a major user of stud welding for attaching shear connectors (Figure 5-67), conduits, piping, electrical switch boxes, and so on, to metal work. The shipbuilding industry uses stud welding for attaching wood decking to metal decking, also for attaching insulation to the interior steel portions of ships. Machinery manufacturers use studs for the attachment of inspection cover plates. The automotive industry uses stud welding for frames and for attaching trim to auto bodies. These installations utilize an automatic stud feeding mechanism.

FIGURE 5-67 Making stud welds on bridge girder.

5-6 OTHER NONCONSUMABLE ARC WELDING PROCESSES

The two other welding processes that utilize the heat of the arc are the atomic hydrogen process, which is rarely used today, and the magnetic rotating arc (MIAB), which is becoming more widely used.

Atomic hydrogen welding (AHW) is an arc welding process that uses an arc between two metal electrodes in a shielding atmosphere of hydrogen and without the application of pressure. Filler metal may or may not be used. Atomic hydrogen welding is no longer of industrial significance.

This process was invented by Irving Langmuir of General Electric Company in the mid-1920's. He found that atomic hydrogen was formed when hydrogen was passed through an electric arc between two tungsten electrodes. Molecular form is the more stable and when the atoms recombine to form molecular hydrogen intense heat is liberated. Figure 5-68 is a diagram of atomic hydrogen process. The arc is maintained between two tungsten electrodes and the hydrogen gas passes from the electrode holder through the arc. The arc stream assumes a fan shape and is characterized by a sharp singing sound. The arc area is usually ⅜ to ¾ in. (9 to 20 mm) in diameter. As the hydrogen passes through the arc, molecules are separated into atoms and this gives the process its name, "atomic hydrogen." As the gas in its atomic state leaves the arc, it recombines to molecular form giving up its heat of disassociation to produce the extremely high welding temperature flame. The arc is independent of the work and can be moved closer to or farther from the work for precise heat control.

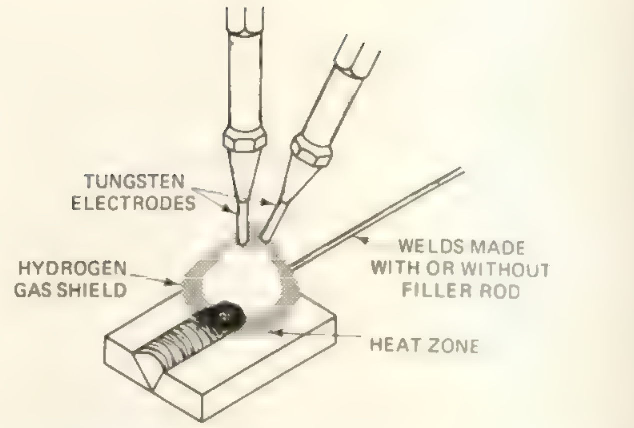


FIGURE 5-68 Atomic hydrogen welding process.

Hydrogen is a very powerful reducing agent and in the presence of the arc and molten metal it tends to reduce any gas-forming material in the arc and thus produce a sound porosity free weld. In addition, the hydrogen prevents contamination of the arc and weld puddle by excluding atmospheric oxygen and nitrogen from the weld area. At one time the process was fairly popular for welding certain hard-to-weld metals such as nickel-base alloys, molybdenum, high-alloy steels, and steels for making tools and dies.

The arc is visible to the welder and welding is done best in the flat and horizontal positions. Safety pre-

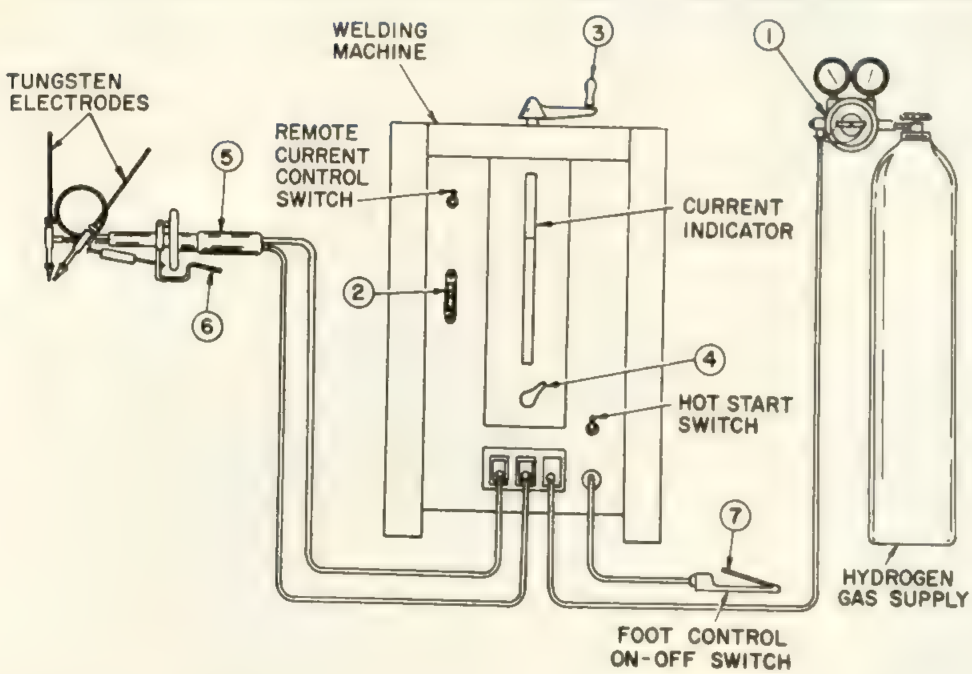
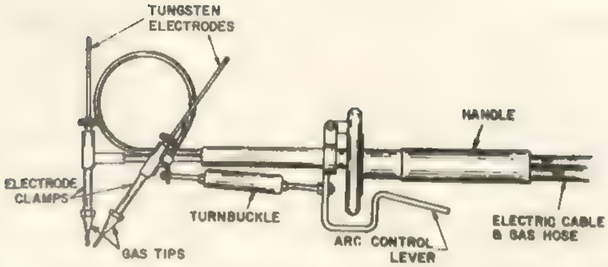


FIGURE 5-69 Atomic hydrogen: circuit diagram.



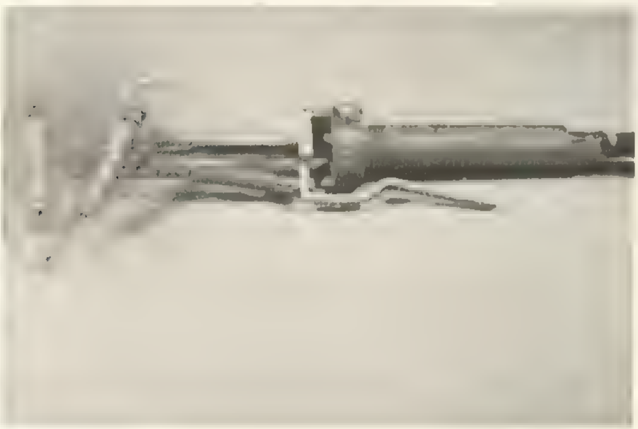


FIGURE 5-70 Atomic hydrogen torch.

cautions must be followed since the open-circuit voltage of the power source approaches 300 V.

The equipment needed for atomic-hydrogen welding is shown in Figure 5-69. The power source has a high open-circuit voltage and for this reason it contains a contactor operated by a foot switch. It also contains a solenoid valve for controlling the flow of the hydrogen gas. The atomic-hydrogen welding torch is shown in Figure 5-70.

Magnetic Rotating Arc Welding

This process is also called Magnetically Impelled Arc Butt (MIAB) welding. It is a relatively new welding process that uses the constant-current power source. It is being applied for welding tubular parts together. The process is a fully automatic process which utilizes a magnetically rotated arc to heat the surfaces to be welded and then utilizes pressure for consummating the weld.[13] The sequence of operations is shown in Figure 5-71. First two tubular parts are clamped in the welding machine. They are moved together until they touch and a hinged magnetic coil is placed around the joint. The welding current is initiated and the parts moved slightly away from each other. The arc is struck, normally by a high-frequency discharge, and the arc is then caused to rotate by the magnetic field in the coil around the parts. The length of time that the arc rotates is in the order of ½

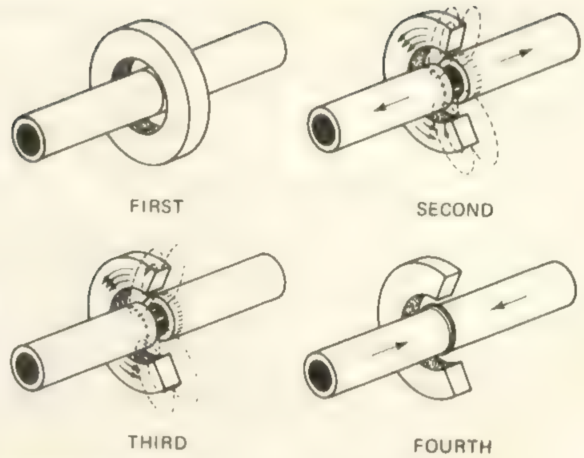


FIGURE 5-71 Magnetic rotating arc welding.

to 2 seconds, depending on the mass of metal to be heated. A shielding gas, normally CO_2, is used to protect the arc and the molten metal from the atmosphere. Pressure is applied bringing the parts together, extinguishing the arc and making a forge weld. The maximum welding current employed is 1000 A and the maximum pressure is on the order of 500 lb.

The process is capable of welding many different metals; however, mild steel, alloy steels, and stainless steels are the only metals currently being welded. The parts do not need to be circular.

One of the advantages is that it is completely automatic and uses less power than would be required by resistance welding. The rotating arc process does not require as much material to be consumed as does flash welding. It is expected that this process will find increasing use in the mass production or high-volume industries. Currently, it is being used to join the cap on the end of a tube to manufacture shock absorbers (Figure 5-72).

FIGURE 5-72 Magnetic rotating arc weld.

QUESTIONS

5-1. How does a nonconsumable arc allow you to make a weld?

5-2 What is the polarity of maximum heat for tungsten to work arc?

5-3. What shielding gas provides a higher arc voltage?

5-4. What polarity provides for cathodic cleaning of the work piece?

5-5- Where is the maximum voltage drop in the nonconsumable arc?

5-6. What is the approximate temperature of the GTAW arc?

5-7. Why is tungsten used in the nonconsumable welding arc?

5-8. Should CO_2 be used with a tungsten arc?

5-9. In GTAW the filter metal is added by a separate rod. How does this minimize spatter?

5-10. What is the major advantage of gas tungsten arc welding?

5-11. What are the disadvantages of gas tungsten arc welding?

5-12. Why is alternating current used for welding aluminum?

5-13. What determines the size of the tungsten electrode?

5-14. Why is stand-off distance less critical for PAW than GTAW?

5-15- Explain the difference between "keyhole" and melt-in mode.

5-16. Must the plasma arc torch always be water cooled? Why?

5-17. Why is carbon arc welding becoming less important industrially?

5-18. True or false: Arc stud welding is a combination of arc and forge welding.

5-19. Explain the difference between arc stud and the discharge variations.

5-20. What is MIAB welding? Where is it used

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6

Arc Welding with a Consumable Electrode

OUTLINE

6-1 THE CONSUMABLE WELDING ARC

In the consumable electrode welding arc, which is the second basic type of welding arc, the electrode is melted and the molten metal is carried across the arc gap. Theoretically, a uniform arc length is maintained between the melting end of the electrode and the weld pool by feeding the electrode into the arc as fast as it melts. The physics of the consumable electrode welding arc is much more complex than that of the nonconsumable arc described in Chapter 5.

The arc welding processes that use a consumable electrode are: shielded metal arc welding, gas metal arc welding, flux-cored arc welding, electrogas welding, and submerged arc welding.

The main function of the arc is to produce heat. It also produces a bright light, noise, and ionic bombardment, which removes the surface of the base metal. The

consumable electrode welding arc, also known as a "metallic arc," is a sustained high-current low-voltage electrical discharge through a highly conductive plasma that produces sufficient thermal energy which is useful for joining metals by fusion.

The consumable electrode welding arc (Figure 6-1) is a steady-state condition maintained at the gap between the tip of the melting electrode and the molten pool of the workpiece. The electrode is continuously fed into the arc and is melted by the heat of the arc. The molten metal of the electrode transfers across the arc gap to the workpiece, where it is deposited and upon solidification becomes the deposited weld metal. This is a very complex operation that is not completely understood.

The consumable electrode welding arc is a column of electrically and thermally excited gas atoms and ionized metal vapors from the electrode material known as a plasma. This plasma conducts current ranging from a few amperes to hundreds of amperes of either alternating current or direct current of either polarity. It has a voltage or potential drop of from 10 to 50 V. The plasma operates at a very high temperature, approximately 6000 °C (10,000 °F). A consumable electrode welding arc has a "point-to-plane" geometric configuration. Details of the arc region are shown in Figure 6-2.

In the metallic arc the high-temperature plasma causes the gas atoms in the arc to break down into positive ions and negative electrons. Electrons (negative) move from the cathode (negative) to the anode (positive). The ions (positive) move from the anode (positive) to the cathode (negative). In direct-current reverse-polarity (DCEP) gas metal arc welding, the common welding polarity, the electrons move from the workpiece to the electrode, and the positive ions move from the electrode

FIGURE 6-1 Consumable electrode welding arc.

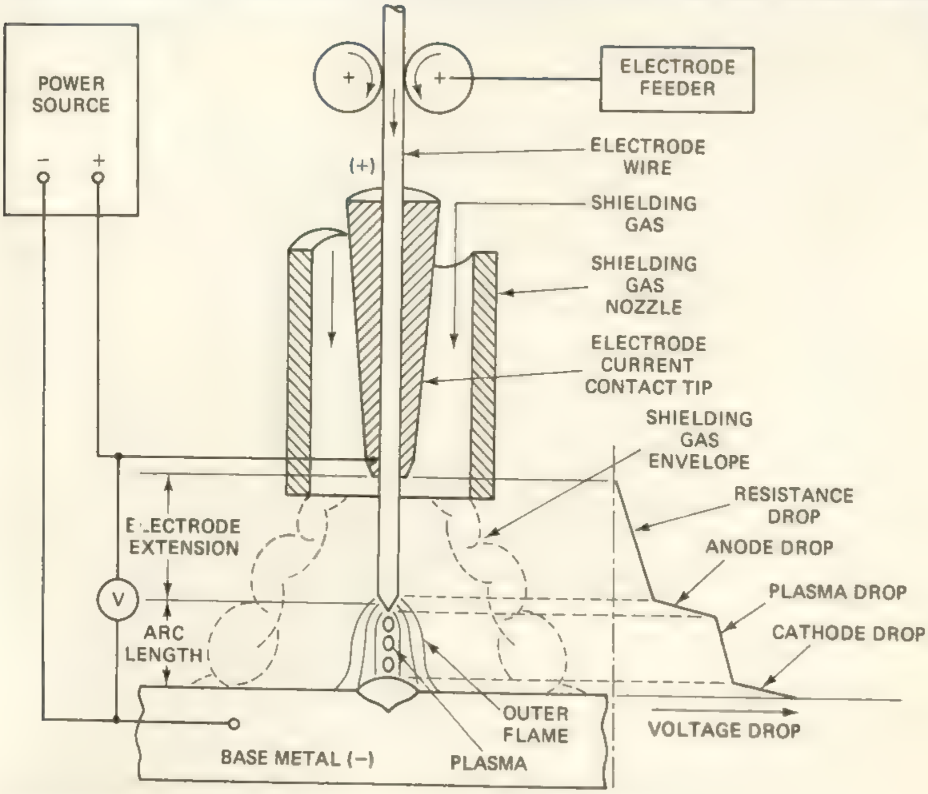


FIGURE 6-2 Arc region of the consumable electric arc

to the workpiece. The largest portion of current flow is carried by the electrons. Conventional current flows from the electrode to the workpiece.

The potential gradiant along the axis of the arc is not uniform. The three voltage regions, known as the anode drop, the arc column or plasma drop, and the cathode drop, are also shown by the figure. The anode and cathode drops are extremely short in length but represent the largest gradient of the voltage potential. The total voltage potential in the arc is the sum of these three potential drop regions.[1] The theoretical arc heat energy available is governed by the welding current and the voltage drops of these three regions. Unfortunately, this is difficult to measure since a voltage meter, in a normal gas metal arc welding system, measures the voltage from the electrical current contact tip to the base metal workpiece. In the total arc region there is another potential drop known as the electrode resistance drop. This is the resistance to current flow through the electrode extension or stickout. This represents a fairly large drop based on the welding current, the diameter of the electrode, and the electrode composition. It is calculated as: electrode resistance drop $E = I^2 \times R$; I is the welding current and R is resistance of the electrode wire for the length of the extension. The heating of the electrode extension has a great effect on burn-off rates.

The relationship between welding current and arc voltage is not a straight line. The curve shown in Figure 6-3 is nonlinear and in the low-current area has a negative slope.[2] The major part of the curve shows that the arc

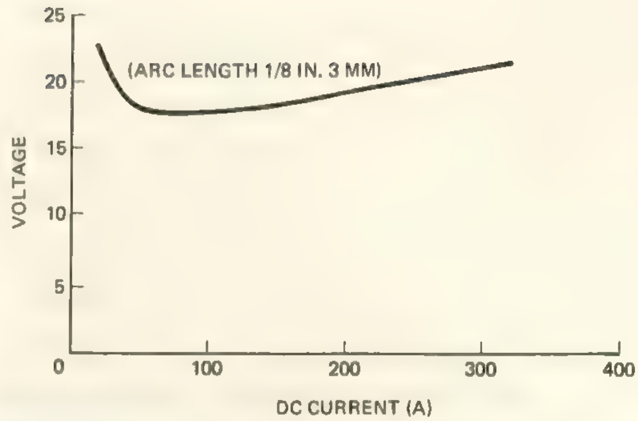


FIGURE 6-3 **Arc voltage versus welding current of the metal arc in argon. (From Ref. 2.)**

voltage does increase with welding current, other conditions remaining the same. The welding current can be varied over a wide range of values from at least 20 A to over 500 A direct current.

The length of the arc, or the arc gap, affects the arc voltage. A short arc which is approximately equal to one diameter of the electrode wire has the lowest voltage. The medium-length arc is in the medium-voltage range. The long arc is equal to about five times the diameter of the electrode and has the highest voltage. This is shown in Figure 6-4, which shows an aluminum arc in helium. The long arc becomes uncontrollable and it will not

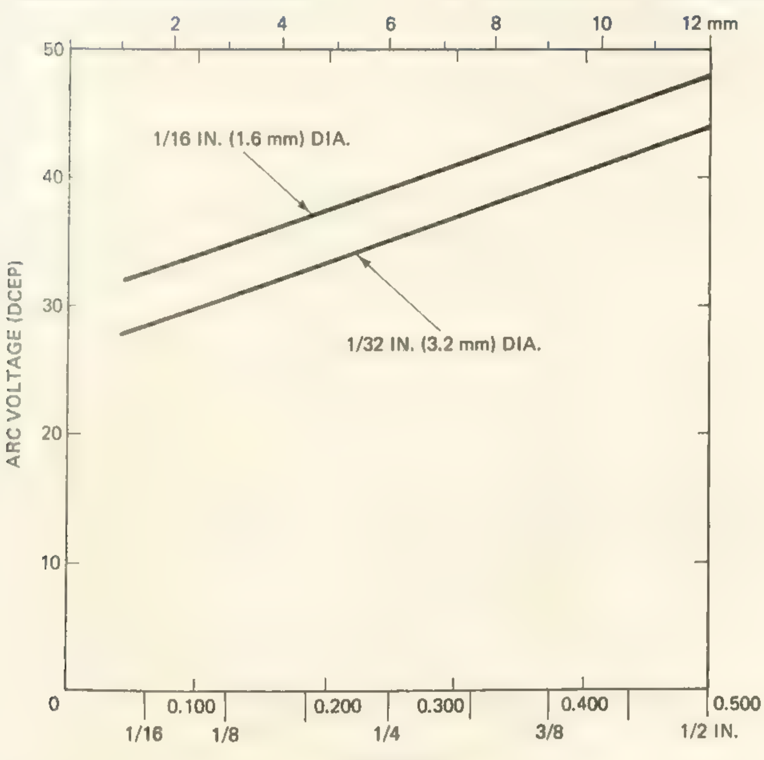


FIGURE 6-4 **Arc length–arc voltage relationship. (From Ref. 3.)**

deposit metal. If the gap becomes too long, the arc will go out; however, higher currents will sustain a longer arc length. If the gap is too short, the arc will short out. With covered electrodes a higher current allows a shorter arc.

The arc atmosphere affects arc voltage. Figure 6-5 shows effect of argon and helium gas on the arc length and arc voltage when welding on aluminum.[3] This relationship would apply to different metals. This can be shown in another way by Figure 6-6, which shows the arc volts and welding current for argon, argon + 5% oxygen, and helium when welding steel.[4] With a higher arc voltage based on the shielding atmosphere, a hotter arc will result. This increases the thermal energy in the arc, which will slightly increase the melt-off rate of the electrode. This is a minor factor in determining burn-off rates.

Good-quality welding and high-productivity welding depend on two major factors, the penetration of the weld into the base metal and the melt-off rate of the electrode. Figure 6-7 shows the polarity and heat relationship for gas metal arc and for shielded metal arc welding. The polarity of maximum heat in a metallic welding arc depends on the polarity and the arc atmosphere. In shielded metal arc (covered electrode) welding the arc atmosphere depends on the composition of the coating on the electrode. The maximum heat normally occurs at the negative pole (cathode). When straight-polarity welding (DCEN) with an E6012 elec-

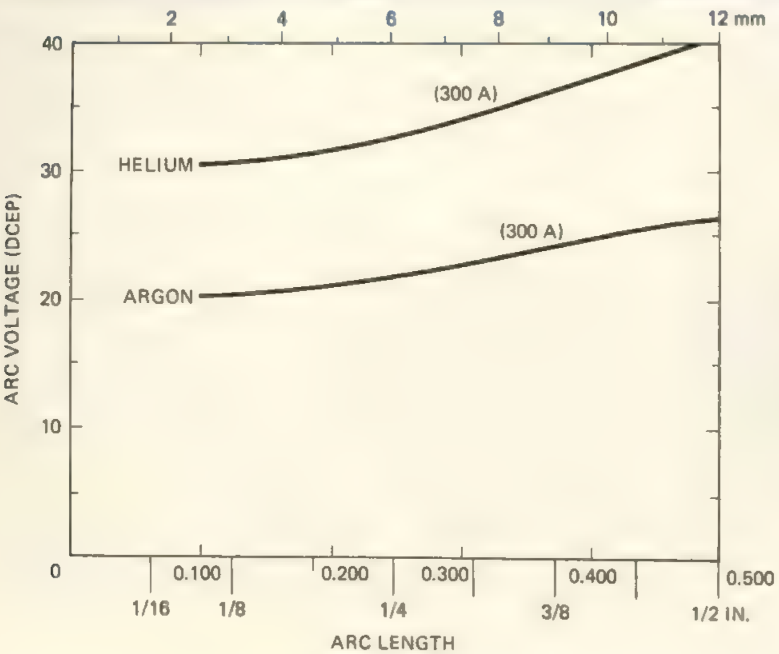


FIGURE 6-5 Arc length–arc voltage in different atmospheres. (From Ref. 3.)

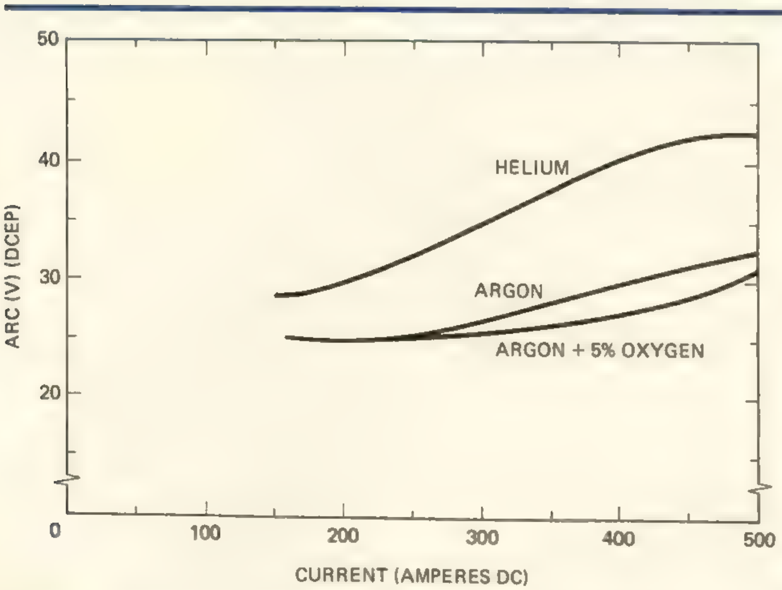


FIGURE 6-6 Arc voltage–welding current in different atmospheres. (From Ref. 4.)

trode, the electrode is the negative pole and the melt-off rate is high, but the penetration of the base metal is low. When reverse-polarity welding (DCEP) with an E6010 electrode, the maximum heat still occurs at the cathode (negative pole), but this is now the base metal, where deep penetration occurs. With a bare steel electrode on steel in air the polarity of maximum heat is the anode (positive pole). This is why in the early days bare electrodes were operated on straight polarity (DCEN) so that adequate penetration would result. When coated electrodes are operated on alternating current (ac), the same amount of heat is produced at each polarity of the arc.

The same characteristics are exhibited by the gas metal arc welding process. Direct-current electrode negative is normally used only with an emissive electrode wire, which is not very popular in the United States. This is because the emissive coated electrode wire has a relatively short storage life.

The relationship between melt-off rates and polarity for metallic arc welding is shown in Figure 6-8. The melt-off rate with reverse polarity (DCEP) is lower than when straight polarity is used. Submerged arc welding is shown in part[5] and gas metal arc welding is shown in part[6]. This shows a $3/32$-in. (3.2-mm)-diameter steel electrode wire and approximately $1/4$-in. (6.3 mm) arc length. The higher melting rates occurring when the electrode is negative (straight polarity) can be up to 50% faster. Dc straight or reverse polarity or ac welding for submerged arc is very

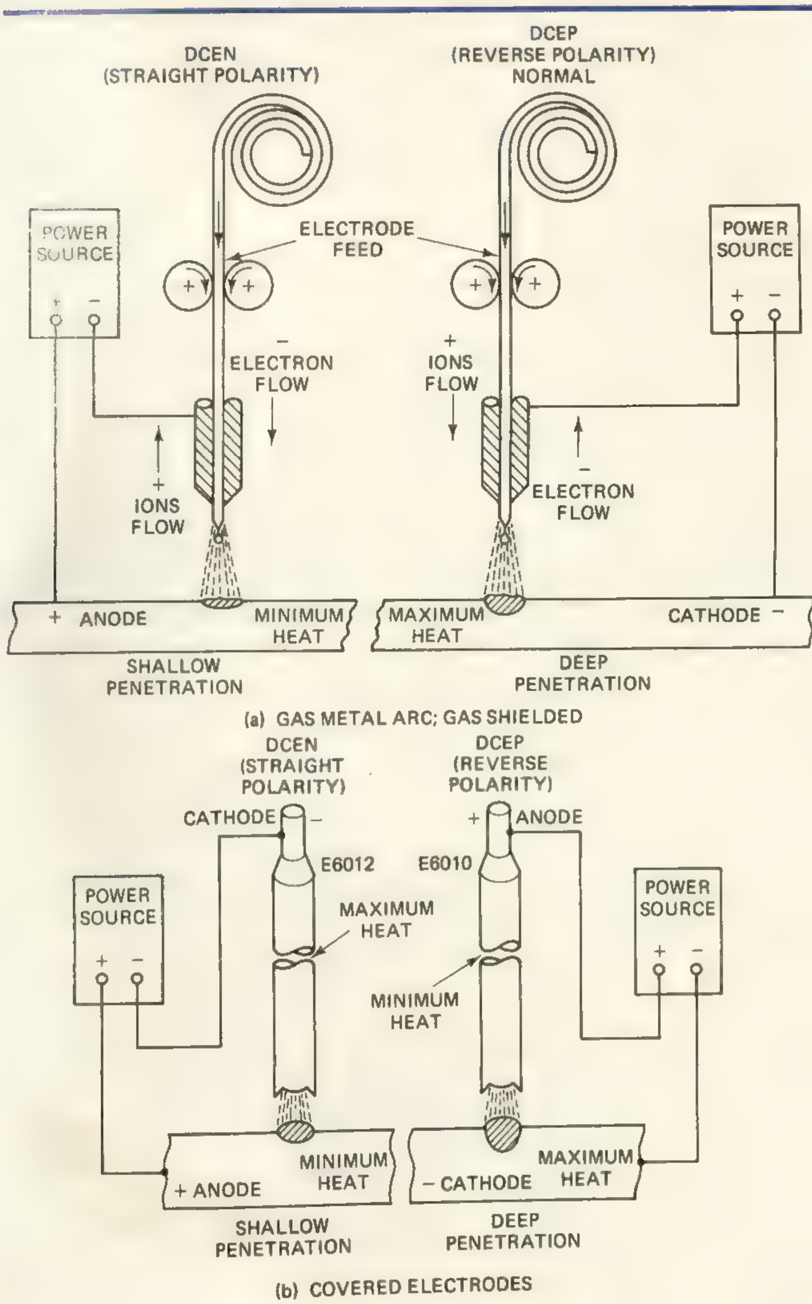


FIGURE 6-7 Metallic arc showing polarity and heat.

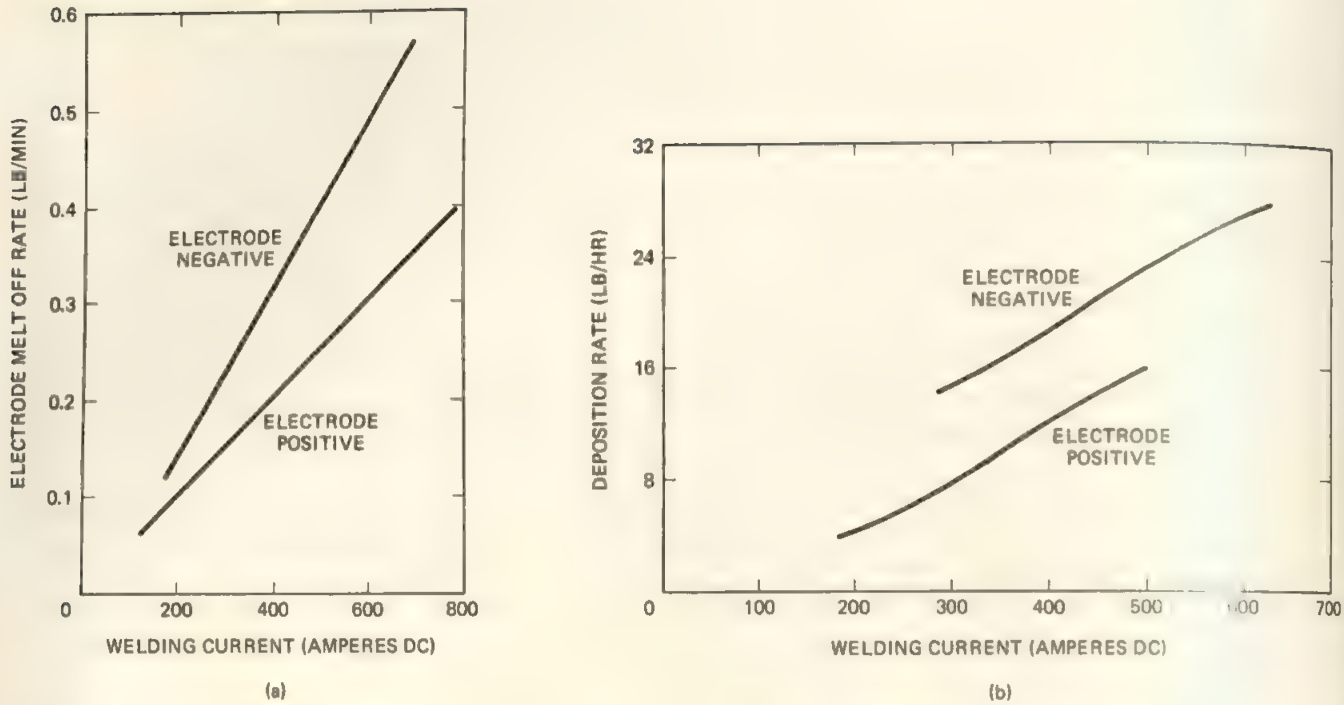
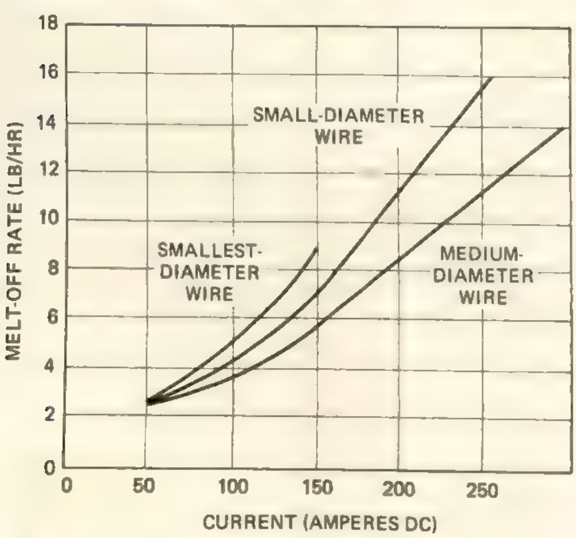


FIGURE 6-8 Melt-off and deposition rates versus polarity for steel. (From Refs. 5 and 6.)

common. Straight polarity (DCEN) with gas metal arc welding is not common but is used with flux-cored arc welding. Alternating-current (ac) welding is impossible using a sinusoidal waveform with GMAW or FCAW.

Welders soon learn that when using high current the electrode is metled off rapidly, and when using low current the electrode melts off slowly. This relates to the thermal energy or power in the arc and arc area. This basic relationship, shown in Figure 6-9, applies to all the consumable electrode welding processes. The thermal energy produced in the arc is the product of the welding current and the arc voltage. It is a measure of work that can be performed. The thermal energy is used to melt the base metal to provide weld penetration and to melt the welding electrode, and in addition, it heats the atmosphere, especially the welding gun, the gas nozzle, and the contact tip. The heat required to melt the electrode is a physical relationship between the current and the weight of metal melted. This is known as melt-off rate or burn-off rate, which is the weight of metal melted per unit of time. The deposition rate is the weight of metal deposited per unit of time and takes into consideration spatter and slag losses.

FIGURE 6-9 Melt-off rates versus welding current (DCEP).



There are a number of factors that affects the melt-off rate. Most important is the melting point of the material. For example, aluminum, with a low melting temperature, will have a high linear burn-off rate. However, the weight of material depends on its density; hence a high linear burn-off rate (wire feed speed) does not necessarily mean a high deposition rate based on pounds per hour. Steel has a higher melting temperature but has a greater density. Melt-off rates for different metals and electrode sizes are shown in Figure 6-10.

The size of the electrode wire also has an effect. This is based on the current density, which is the welding current divided by the cross-sectional area of the electrode wire. Figure 6-11 shows the current density versus sizes of electrodes. This seems to be contradictory to an earlier statement, but is because of the heating in the electrode extension. Current density also has an effect on depth

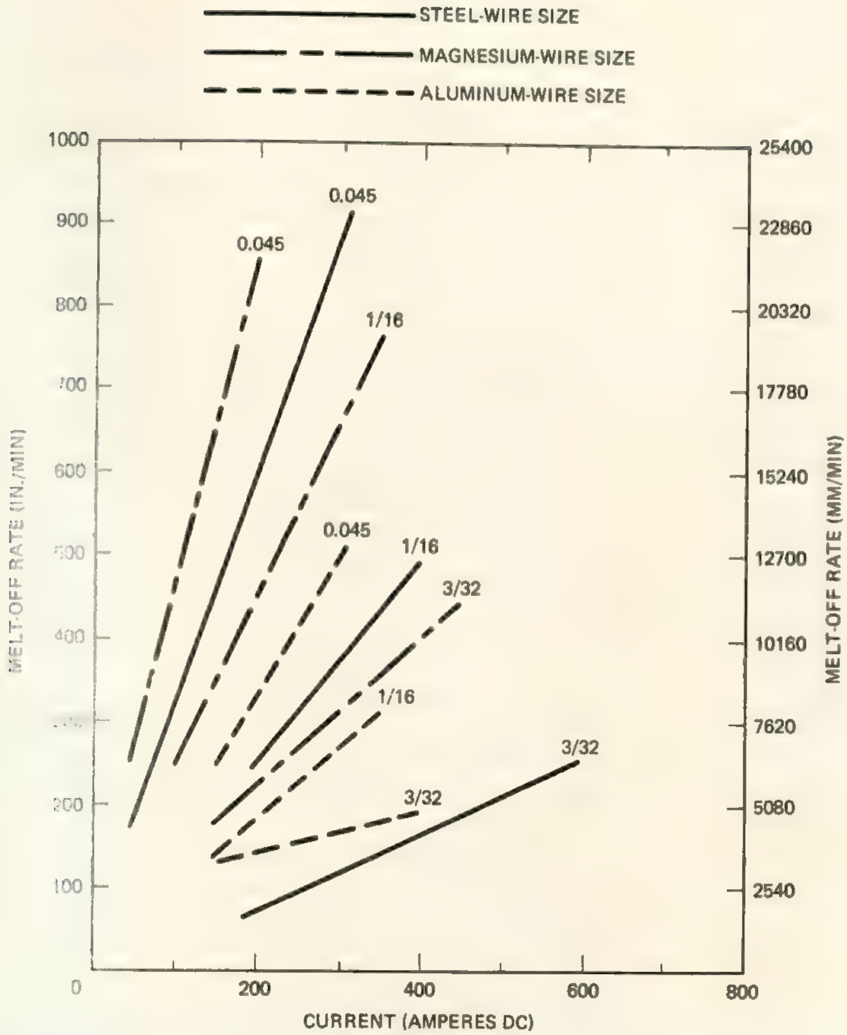
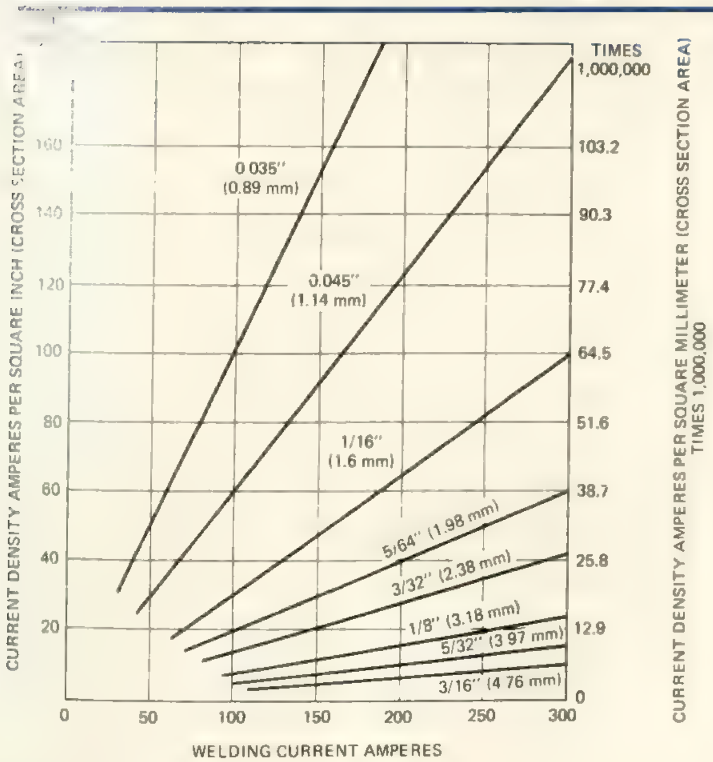


FIGURE 6-10 Melt-off rate for different metals and electrode sizes.

FIGURE 6-11 Current density for different electrode diameters.

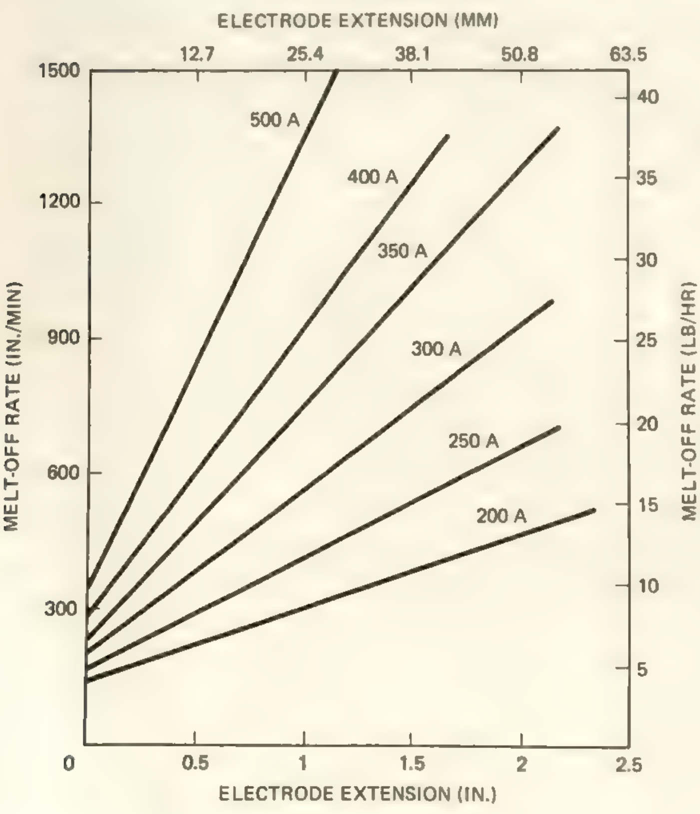


of penetration. The smaller the electrode diameter, the higher the current density at the same welding current. At higher current densities the melting rate increases for the same current, which explains the divergence of the curves in the melt-off rate versus welding current curve.

The other factor that has a major contribution to melt-off rate is the effect of the electrode extension. This is the heating, by resistance, of the electrode extension. This heating can be called self-preheating and is a technique used to increase deposition rates. The effect of electrode extension and welding current on the melt-off rate is shown in Figure 6-12.[7] This shows that melt-off rate is dependent on both factors, which are interrelated.

The heat generated in this extension can be quite high and will cause the electrode wire to lose its stiffness between the contact tip and the arc. Special nozzle adapters or extended pickup tips are often used. These are electrode wire guides with insulation so that the current is introduced at the pickup tip but the extension keeps the electrode pointed in the proper direction. Too much preheating will reduce the penetration of the arc. Electrode extension is very useful with the flux-cored arc welding process. It preheats the electrode and drives off hydrogen that might be present due to moisture of the ingredients or drawing compounds. Special nozzles, as mentioned above, are quite popular for dc electrode negative (straight polarity) welding with self-shielding flux-cored electrode wires.

FIGURE 6-12 Electrode extension related to current and melt-off rate. (From Ref. 7.)



In all the consumable electrode arc welding processes a stable arc is required for successful operation. A stable sustained metallic arc is obtained only when the melting rate of the electrode is equal to the feed rate of the electrode into the arc. This applies whether feeding is done manually as with coated electrodes, or mechanically with the other consumable electrode arc welding processes. The effect of other variables, such as electrode angle, travel speed, and work position, are discussed later in the chapter.

6-2 METAL TRANSFER ACROSS THE ARC

The forces that cause metal to transfer across the arc are similar for all the consumable electrode arc welding processes. The metal being transferred ranges from small droplets, smaller than the diameter of the electrode, to droplets much larger in diameter than the electrode. The mechanism of transferring liquid metal across the arc gap is controlled by surface tension, the plasma jet, gravity, and electromagnetic force, which provides the pinch effect.[8] It is a combination of these forces that acts on the molten droplet and determines the transfer mode.

Surface tension of a liquid causes the surface of the liquid to contract to the smallest possible area. Surface tension tends to hold the liquid drops on the end of a melting electrode without regard to welding position. This force works against the transfer of metal across the arc. It also helps keep molten metal in the weld pool when welding in the overhead or vertical positions.

The arc contains a plasma jet which flows along the center of the arc column between the electrode and base metal. Molten metal drops in flight are accelerated toward the work piece by the plasma jet. Under some conditions the plasma jet may interfere with the transfer of metal across the arc gap.

Earth's gravity tends to detach the liquid drop when the electrode is pointed downward and is a restraining force when the electrode is pointing upward. Earth's gravity has a noticeable effect only at low welding currents. The difference between the mass of the molten metal droplet and the mass of the workpiece has a gravitational effect which tends to pull the droplet to the larger mass, the workpiece. An arc between two electrodes will not deposit metal on either one.

Electromagnetic force creates the pinch effect force, which helps transfer metal across the arc. When the welding current flows through the electrode, a magnetic field is set up around it. Electromagnetic force acts on the liquid metal drop when it is about to detach from the electrode. As the metal melts, the cross-sectional area of the electrode changes at the molten tip. The electromag-

netic force acts to detach a molten drop at the tip of electrode tip. When the molten drop is larger in diameter than the electrode, the magnetic force tends to detach the drop. When there is a constriction, or necking down, which occurs when the molten drop is about to detach, the magnetic force acts away from the point of constriction in both directions and the drop, which has started to separate, will be given a push which increases the rate of separation. This is known as the *pinch force* (Figure 6-13). Pinch force is proportional to the square of the current. Figure 6-14 is a series of high-speed movie photographs of the welding arc. Part (a) shows the start of the constriction, part (b) shows the droplet just before separation, and part (c) and (d) show the drop in free flight across the arc gap. The rate of change of welding current can regulate the strength of the pinch effect. This is determined by slope of output current of the machine but more dramatically by pulsing the current which controls the detachment of liquid drops from the end of the electrode.

Magnetic forces also set up a pressure within the liquid drop. The maximum pressure is radial to the axis of the electrode and at high currents causes the drop to become elongated. It gives the drop stiffness and causes it to project in line with the electrode, regardless of the welding position.

The mode of metal transfer across the arc is related to the welding process; the metal involved; the arc atmosphere; the size, type, and polarity of the electrode; the characteristics of the power source; the welding position, and the welding current, current density, and heat input. In gas metal arc welding, reverse polarity (DCEP) is normally employed. For straight polarity (DCEN), an emissive coating is often placed on the electrode surface.

Metal transfer can be defined as "free flight" transfer mode, which includes spray and globular transfer, or "contact" atmosphere mode, which includes short-circuiting transfer. The most common way to classify metal transfer is according to size and frequency and characteristics of the metal drops being transferred. There are four major types of metal transfer:

1. Spray transfer
2. Globular transfer
3. Short-circuiting transfer
4. Pulsed-spray metal transfer

These types of metal transfer are well defined. There is an intermediate form of transfer in the transition zone between two modes where both types of transfer may occur simultaneously. The stability of the welding arc and the metallurgical changes in the weld metal are dependent on the metal transfer mode. Welding procedures are grouped according to the metal transfer mode.

Spray Transfer

The transition between the globular mode and the spray transfer mode occurs in the mid-200-A range on carbon steel. This is based on the size of the electrode and the current density. This transition range of a mild steel electrode in an atmosphere of 95% argon + 5% oxygen is shown in Figure 6-15. In the range below the transition or full spray mode, the drops of molten metal are approximately the same size as the electrode wire. In this transition mode, metal transfer is not as smooth and there is more spatter. The frequency of drop detachment is

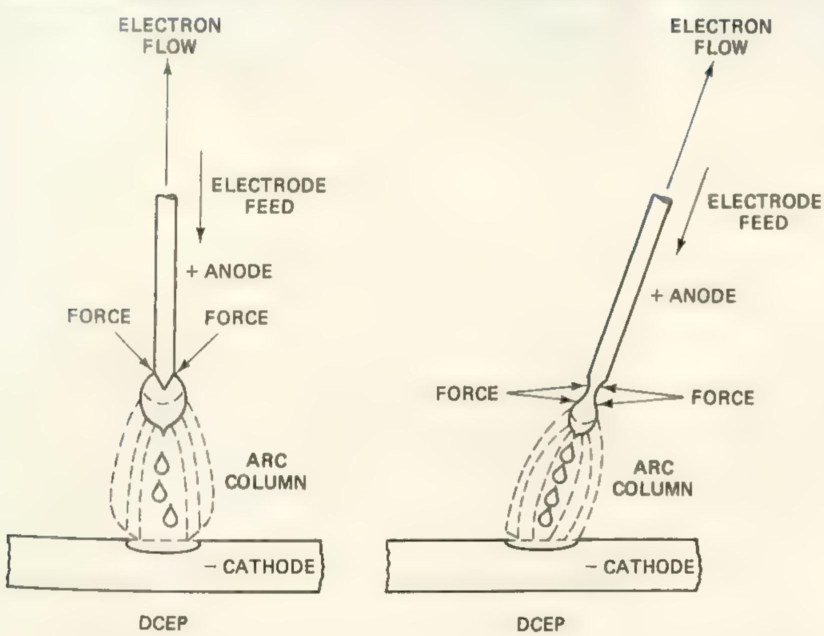


FIGURE 6-13 Electromagnetic force on drop about to transfer.

FIGURE 6-14 High speed photographs of metal transfer.

regular and at a higher frequency than globular transfer.[9]

Spray transfer, sometimes called axial spray, is a very smooth mode of transfer of molten metal droplets from the end of the electrode to the molten weld pool. It was the original type of metal transfer used when gas metal arc welding was initially developed. Spray transfer is shown graphically in Figure 6-16. Spray transfer occurs in an inert gas atmosphere, usually with a minimum of 80% argon shielding gas. The droplets crossing the arc are smaller in diameter than the electrode. The tip of the electrode is pointed. It occurs at a relatively high current density and there is a minimum current level for each electrode size. As the current increases, the drop size decreases and the frequency of drops increases. The drops have an axial flow, which means that they follow the centerline of the electrode and travel directly to the weld pool. There is no short circuiting in spray transfer. The electromagnetic forces are the dominant forces due to the high current density. The pinch effect on the molten tip of the electrode physically limits the size of the molten metal droplet that can form. Therefore, only small droplets are formed, which transfer across the arc at relatively high frequency. With spray transfer the deposition rate and efficiency is relatively high. The arc is very smooth, stable, and stiff and the weld bead has a nice

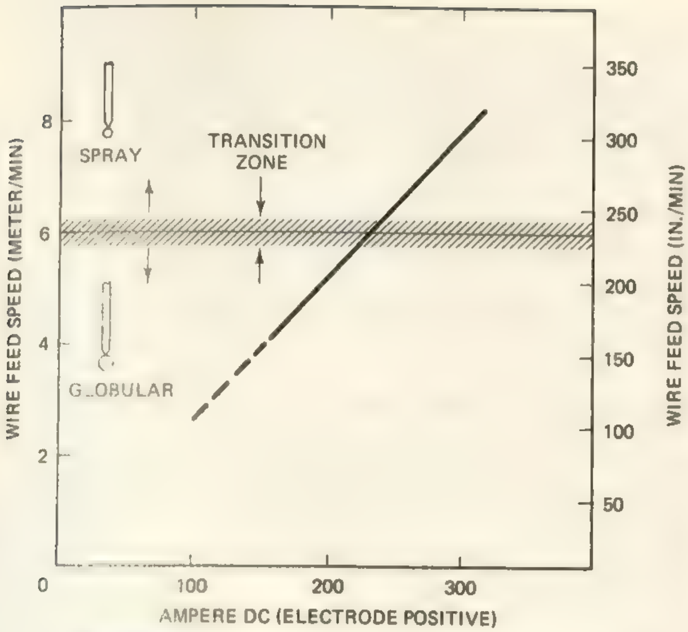


FIGURE 6-15 Transition zone between spray and globular modes.

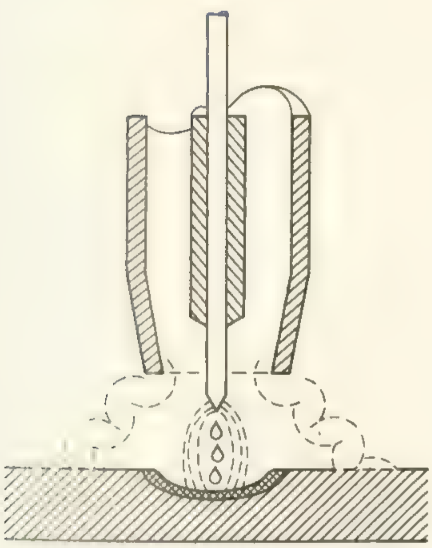


FIGURE 6-16 Spray transfer metal transfer mode.

appearance and a good wash into the sides. Spray transfer is shown by high-speed photographs in Figure 6-17.

In spray transfer a large amount of heat is involved, which creates a large weld pool with good penetration that can be difficult to control. Thus normal spray transfer is limited to the flat and horizontal positions and is not used to weld thin materials. As current is increased beyond axial spray transfer range, the line of metal drops begins to rotate rapidly about the axis of the electrode, still leaving from the tip of the electrodes. As current is increased further, the diameter of rotation increases and

FIGURE 6-17 High-speed photographs of spray transfer mode.

spatter increases. This is known as rotational spray transfer. The solution to this is to use a larger-diameter electrode or decrease the current.

Globular Transfer

Below the transition level the metal transfer mode is called globular transfer and is shown graphically in Figure 6-18. This type of transfer usually occurs when CO_2 shielding gas is used. It was a type of metal transfer originally encountered with the development of CO_2 gas-shielded

FIGURE 6-18 Globular transfer metal transfer mode.

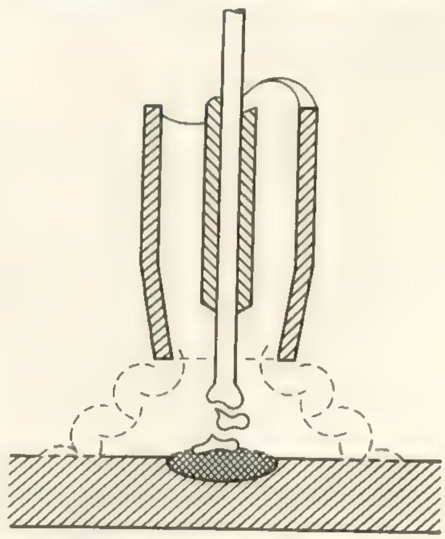


FIGURE 6-19 High-speed photographs of globular transfer mode.

welding. High-speed photos of globular metal transfer are shown in Figure 6-19.

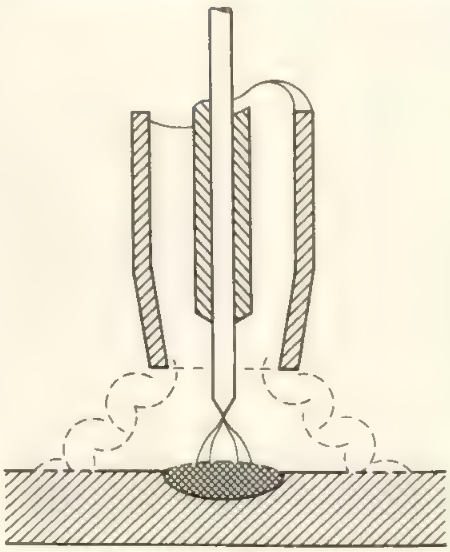
There are several variations of globular transfer, one known as drop transfer, where gravity is the dominant force, one known as the repelled transfer, where forces due to the plasma jet occur even though gravity force is a factor.

Arcs in a CO_2 atmosphere are longer than those in an argon atmosphere; hence the voltage is higher. The "cathode jet" is involved and the electrode is positive (anode). The cathode jet originates from the workpiece (cathode) and actually supports the molten drop of metal on the tip of the electrode. The molten globule can grow in size until its diameter reaches 1½ to 3 times the diameter of the electrode, due to this repelling force. When the globule grows on the tip of the electrode, it takes on unusual shapes and moves around on the tip of the electrode. It separates from the electrode and is transferred across the arc by electromagnetic and gravity forces. The globule transfers across the arc in an irregular path. It changes its irregular shape during flight and sometimes has a rotating motion. The irregular shape, motion, and flight direction sometimes cause the globule to reconnect with the electrode and touch the work as well. This causes a short circuit which momentarily extinguishes the arc. In the globular transfer mode the drop splashes into the weld pool and produces much more spatter than spray transfer. The spatter comes from the violent molten pool as well as from the metal transferring across the arc. The frequency of globular detachment and flight across the arc is random but of relatively low frequency. It takes place at a relatively low current density. The resulting welding deposit is not as smooth as that produced by spray transfer. It is used primarily in the flat and horizontal positions for welding steel. A variation of globular type transfer is known as the "buried arc." This is obtained by increasing welding current and adjusting the welding voltage so that the tip of the electrode is below the surface of the molten weld pool. The arc is within a cavity generated by the force of the arc. It occurs in a CO_2 arc atmosphere and provides very deep penetration. Spatter is reduced. It is used only in the flat position and is useful when making arc spot welds in heavy steel sections.

Short-Circuiting Transfer

Out-of-position welding and welding on thin materials were extremely difficult, if not impossible, using spray or globular metal transfer. The short-circuiting mode of transfer was introduced in the late 1950s for gas metal arc welding of thin metal and for out-of-position welding.[10] It is a low-energy mode of metal transfer. The short-circuiting transfer mechanism, also called short arc and dip transfer, is shown in Figure 6-20. The mechanism of short-circuiting metal transfer is as follows: The molten tip of the electrode is supported by the cathode jet and may grow to 1½ times the diameter of the electrode. The electrode is feeding at such a high relative rate of speed that the molten tip will periodically come in contact with the molten weld pool. This is a short circuit that creates a bridge across the gap between the electrode and the molten pool and the arc is extinguished. Molten metal is transferred from the electrode by the surface tension of the weld pool, which draws the molten metal of the electrode tip into the molten weld pool. The electrode will then separate from the weld pool and reestablish an arc (Figure 6-21). Occasionally when the electrode contacts the weld pool, the electrode will act

FIGURE 6-20 Short-circuiting transfer mode.



like a fuse and literally explode, due to the high current density. The explosion reestablishes the arc. These conditions continue at a random frequency. These arc outages occur so rapidly that they are not noticed by the human eye. They are, however, caught by high-speed photographs (Figure 6-22).

The short-circuiting mode of metal transfer allows all-position welding and the welding of thin materials. It is obtained with specific welding parameters normally limited to a maximum of 200 A DCEP on a 0.035-in. (0.9-mm) steel electrode and CO_2 or 75% argon–25% CO_2 shielding gas. It uses a constant-voltage (CV) power source with the correct impedance, which provides the proper rate of increase of current during the short circuit to maintain a stable arc. The short-circuiting mode of metal transfer will sometime cause cold lap defects in the weld and may create undercutting if proper technique is not employed. The short-circuiting mode is normally

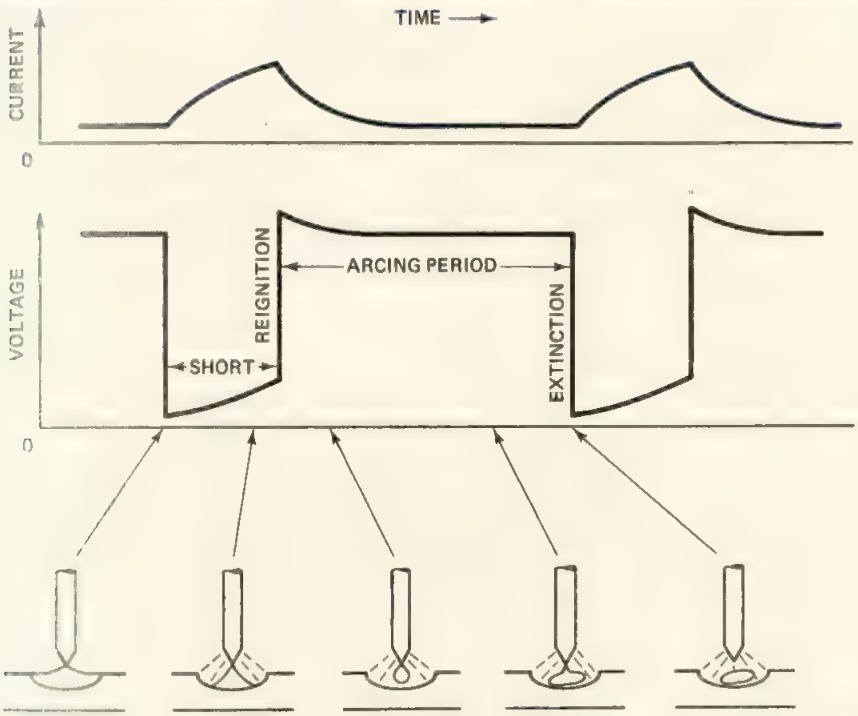


FIGURE 6-21 Short-circuiting transfer mechanism.

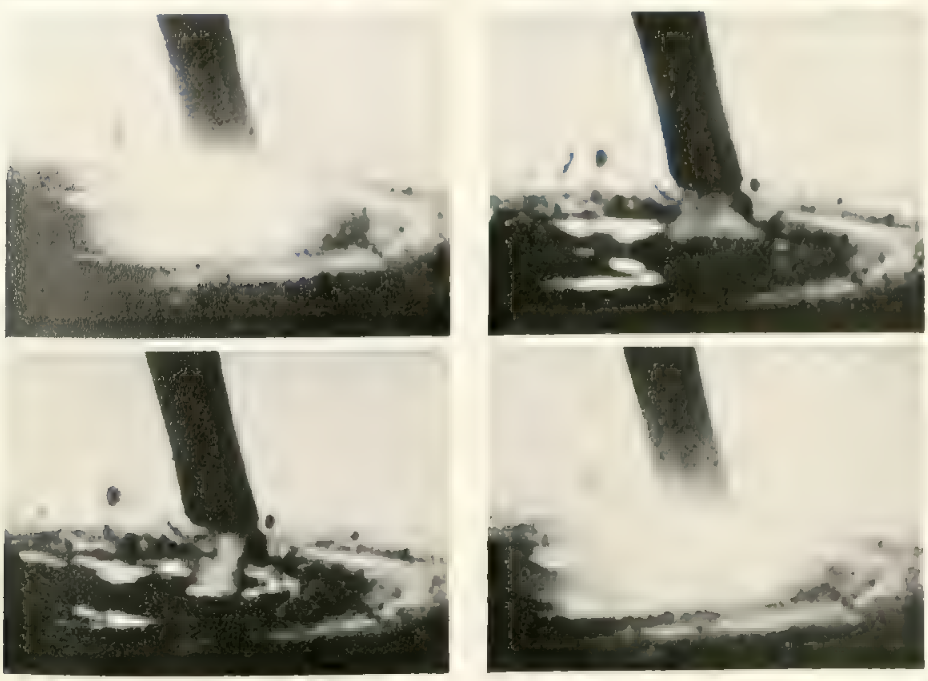


FIGURE 6-22 High-speed photographs of the short-circuiting arc.

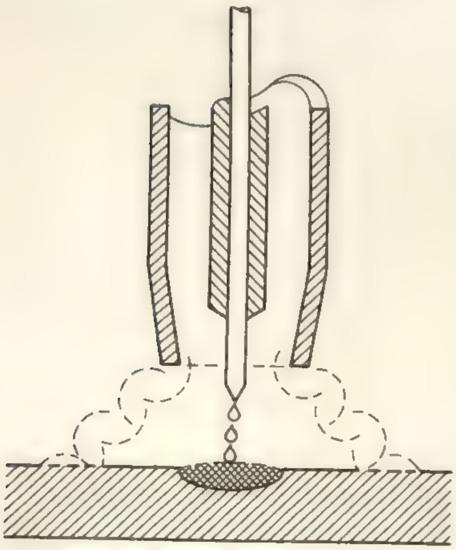
used with CO_2-rich shielding atmospheres and is used basically on ferrous metals. It cannot be used on nonferrous metals.

There is a small amount of spatter involved; however, the weld pool is relatively small and easily controlled. Base metal penetration can be controlled by technique. This mode of metal transfer has the ability to bridge gaps between piece parts that are wider than the thickness of the metal.

Pulsed-Spray Metal Transfer

The pulsed-spray mode of metal transfer was introduced in the late 1960s to overcome the limitations of the three types of metal transfer just mentioned. In the pulsed-spray mode, droplets of molten metal are transferred across the arc at a fixed frequency. Pulsed-spray metal transfer can only be accomplished with a pulsing type of power source. The pulsed-spray transfer mode produces droplets approximately equal to the diameter of the electrode (Figure 6-23). The welding current by a pulsing-type power source varies between a high and a low level (Figure 6-24). The peak or high current level is above the transition current, and the low or background current level has sufficient energy to sustain the arc but not sufficient to transfer metal across the arc gap. The peak or high current pulse supplies extra energy to transfer the molten droplet across the arc. Theoretically, one drop of metal is transferred across the arc at each high current pulse. Thus pulsed-current power achieves the spray transfer mode at a lower average current, which means a lower heat input. This provides a smaller controllable weld pool, which allows the welding of thin materials in all positions. It also allows the use of larger-diameter electrodes than normal. Weld spatter is greatly reduced. Pulsed-spray welding uses argon-rich shielding gases, usually with 1%, 2%, or 5% oxygen in argon. The pulsed transfer mode can be used to weld most metals, including nonferrous metals and some difficult to weld metals. Shielding gases of 5 to 20% CO_2 in argon are used on steels. Pulsed-spray welding produces nice-appearing smooth welds.

FIGURE 6-23 Pulsed-spray transfer mode.



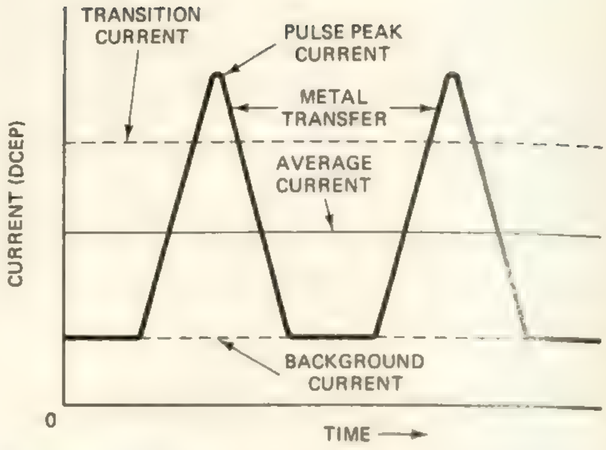


FIGURE 6-24 Mechanism of pulsed-current metal transfer.

In the original pulsed-spray system the frequency of pulsing was at utility-line frequency or double utility-line frequency; normally, it would be 50 or 60 pulses per second, or 100 or 120 pulses per second. Unfortunately, establishing a welding procedure with this equipment was extremely difficult due to the extra number of weld parameters involved. The peak or pulse current and time of pulse duration needed to be established; however, due to the design of the machines, the pulse duration was fixed. Also, the background current had to be balanced with peak current and electrode feed speed in order to obtain proper heat, good arc stability, and proper bead shape. Successful use of pulsed-spray welding depended on the ability of the welder to set up and adjust these variables properly. Due to these difficulties the pulsed-spray metal transfer mode did not become too popular but did indicate the need for a more refined system.

Synergic Pulsed-Spray Metal Transfer The term *synergic* is a Greek word meaning "working together." In synergic welding it means that the optimum pulse peak current and pulse peak current time duration is matched to the background current. The shape of the waveform of the pulse, the duration of the peak pulse, and the pulse frequency are matched to the arc atmosphere and to the electrode feed rate for a given size and type of electrode. The optimum application parameters are tuned into the welding machine by means of a microprocessor and solid-state electronic circuits and a software program. The result is a variable-frequency spray metal transfer mode that produces a controllable weld pool and a smooth weld with virtually no spatter. Furthermore, it can be provided for all weldable metals in any thickness and can be used in any position.

There are two basic types of pulsing power sources available that must be controlled differently. One is a constant-current static characteristic type and the other a constant-voltage static characteristic type (Figure 6-25).

With this type of control the welder or operator has a single knob which allows the average current to be varied from minimum to maximum of the machine rating and still provide the optimum wave shape and frequency for pulsing. The welding pulse frequency will vary in accordance with the particular program, but is optimum for the particular application. Most commerically available machines have the capability of an adjustment to compensate for long or short welding arcs. The constant-voltage types of machine provide this adjustment by varying the pulse width, frequency, or the background current. The constant-current types of machines provide this adjustment by varying electrode wire feed speed. The wire feeder must be matched to the power source. This adjustment does not change the basic metal transfer system.

The synergic mode of metal transfer is precisely regulated. It provides welds that are extremely smooth. This mode of metal transfer is recommended for high-quality, precision welding applications where mechanization, including robotics, is used.

The metal transfer for flux-cored arc welding electrodes is different than for solid electrodes. Metal transfer is different when the core is filled with minerals for atmosphere control and for fluxing than when metal and ferrous alloys are used. The sheath or outer metal part of the electrode carries the welding current. Arcing occurs at the metallic sheath, which starts melting. The core material melts from the heat generated by the arc. The electrode extension portion is preheated, which causes smoother metal transfer. Flux also transfers across the arc and sometimes bridges the gap. The type of transfer does not relate to the welding procedure, which is largely based on electrode diameter, current, and voltage.

The metal transfer across the arc with submerged arc welding is hidden from the human eye. It has been studied, however, and is much similar to the transfer in gas metal arc welding. The metal transfer mode is of less importance for these processes.

The metal transfer across the arc with covered electrodes is somewhat different since several other factors are involved. With the larger-diameter electrodes, the arc does not constantly cover the entire cross section or end of the core wire. The slag formed from the melting of the electrode coating covers a portion of the tip of the core wire. This slag and the atmosphere created by

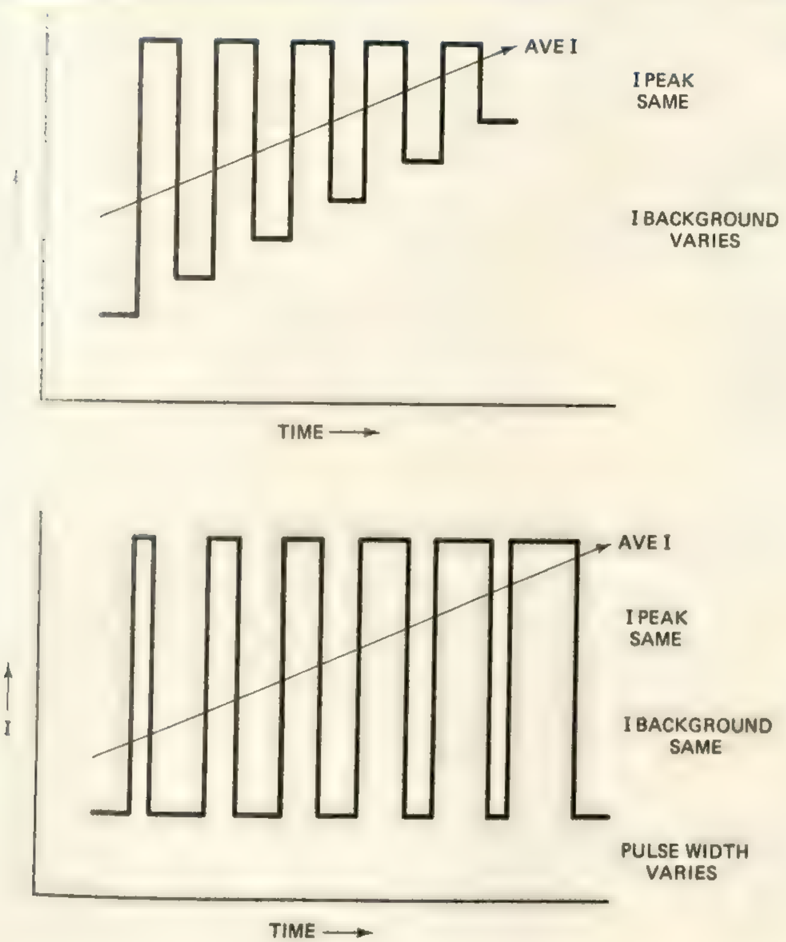


FIGURE 6-25 Synergic pulsed-current machine characteristics.

the burning of the coating affects the metal transfer. The drop size can be rather large up to the diameter of the core wire, or small, much smaller, than the core wire diameter. With heavy-coated lime base (EXX15) electrodes, the metal transfer has fairly large, course drops with short circuits. With the low hydrogen iron powder type (EXX18) and the cellulose (EXX10 and 11) electrodes, relatively large drop transfer occurs. With rutile-type (EXX12) electrodes, relatively fine drop transfer occurs. The droplets are covered with flux during the flight across the arc.

6-3 SHIELDED METAL ARC WELDING

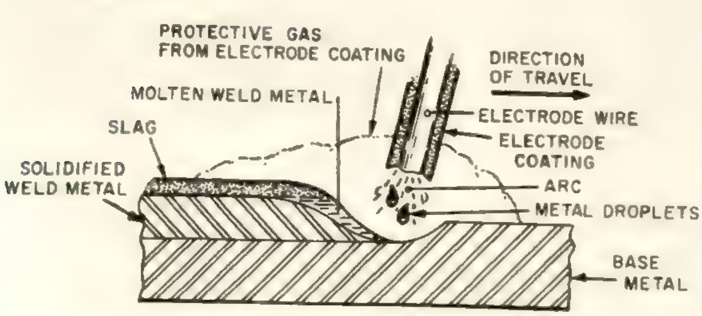
Shielded metal arc welding (SMAW) is an arc welding process with an arc between a covered electrode and the weld pool. The process is used with shielding from the decomposition of the electrode covering, without the application of pressure, and with filler metal from the electrode. It is also known as "stick" electrode welding.

Principles of Operation

The welder's view of SMAW is shown in Figure 6-26. The shielded metal arc welding process (Figure 6-27) consists of an arc between a covered electrode and the base metal.

FIGURE 6-26 Welder's view of SMAW arc.

FIGURE 6-27 Shielded metal arc welding process diagram.



The arc is initiated by momentarily touching the electrode to the base metal. The heat of the arc melts the surface of the base metal to form a molten pool. The melted electrode metal is transferred across the arc into the molten pool and becomes the deposited weld metal. The deposit is covered by a slag which comes from the electrode coating. The arc and the immediate area are enveloped by an atmosphere of protective gas produced by the disintegration of the electrode coating. Most of the electrode core wire is transferred across the arc; however, small particles escape from the weld area as spatter.

Advantages and Major Uses

The shielded metal arc welding process is the most popular arc welding process. It has maximum flexibility and can weld many metals in all positions from near minimum to maximum thickness. The investment for equipment is relatively small and most welders have the necessary skill to use the process. It is used in manufacturing operations and widely used in field work for construction and maintenance.

Method of Application

The normal method of applying SMAW is shown in Figure 6-28. The manual (MA) method of applying shielded metal arc welding is most common and represents 99% of all the use of the process. Semiautomatic (SA) and machine (ME) methods are not used. The automatic (AU) method is used and is called gravity welding but has limited applications.

FIGURE 6-28 Methods of applying (SMAW)

Method of Applying	Rating
Manual (MA)	Most popular
Semiautomatic (SA)	Not used
Machine (ME)	Not used
Automatic (AU)	Possible

Welding Position Capabilities

This process has all-position capabilities (Figure 6-29). Welding in the horizontal, vertical, and overhead positions depends on the type and size of the electrode, the welding current, and the skill of the welder.

Weldable Metals

This process can be used to weld most steels and some of the nonferrous metals. Its major use is for joining steels, including low-carbon or mild steels, low-alloy steels, high-strength steels, quenched and tempered steels, high-alloy steels, stainless steels, corrosion-resistant steels,

and for welding cast iron and malleable irons. It is used for welding nickel and nickel alloys and to a lesser degree for welding copper and some copper alloys. It can be, but rarely is, used for welding aluminum. It is not used for welding magnesium, the precious metals, or the refractory metals. Figure 6-30 shows the weldable base metals. Shielded metal arc welding is also used for surfacing.

Base Metal Thickness Range

The range of thickness of base metal normally welded by the shielded metal arc welding process is shown in Figure 6-31. The minimum thickness that can be welded is largely dependent on the skill of the welder. Steel of 1/16 in. (1.6 mm) can be welded by a skilled welder. Thinner material takes extra skill and special precautions. Steel up to 1/4 in. (6.4 mm) can be welded without the necessity of groove welds if sufficient root opening is provided. Thicker material requires joint preparation and multiple passes are required. The largest fillet weld that can normally be made in the horizontal position is 5/16 in. (8 mm). In the vertical position larger fillets can be made; however, quality deteriorates if fillets are made over 3/8 in. (10 mm) in a single pass. Maximum thickness is practically unlimited but requires multiple-pass technique.

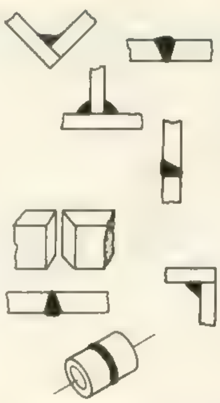
Joint Design

When welding materials thicker than 1/8 in. (3.2 mm) space must be made available to deposit the weld metal. Various weld groove designs are used but the fillet is the most common weld made. Complete information on joint design for the shielded metal arc welding process is given in Chapter 19.

Welding Circuit

Figure 6-32 shows the circuit diagram for shielded metal arc welding. It shows the welding cables used to conduct the welding current from the power source to the arc. The electrode lead forms one side of the circuit and the work lead is the other side of the circuit. They are attached to the terminals of the welding machine.

FIGURE 6-29 Welding position capabilities (SMAW).



Welding Position	Rating
1. Flat	A
Horizontal fillet	A
2. Horizontal	A
3. Vertical	A
4. Overhead	A
5. Pipe – fixed	A

FIGURE 6-30 Metals weldable (SMAW).

Base Metal	Weldability
Aluminums	Possible but not popular
Bronzes	Weldable
Copper	Possible but not popular
Copper nickel	Acceptable
Cast and malleable iron	Weldable
Wrought iron	Weldable
Inconel	Weldable
Nickel	Weldable
Monel	Weldable
Low carbon steel	Weldable
Low alloy steel	Weldable
High and medium carbon	Weldable
Alloy steels	Weldable
Stainless steels	Weldable

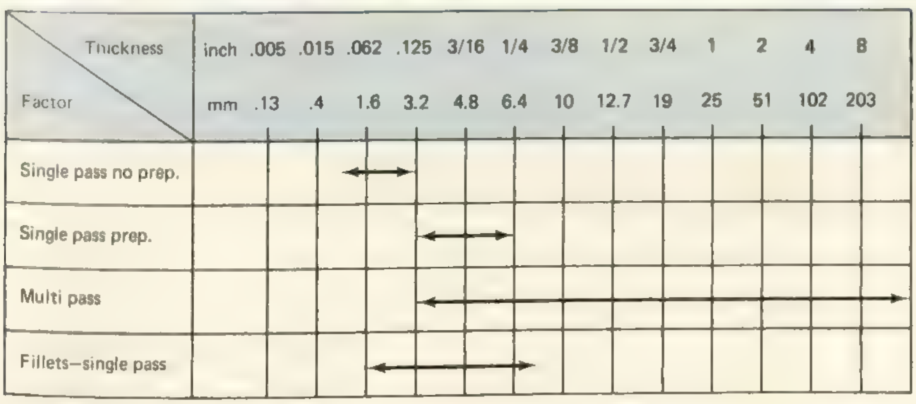


FIGURE 6-31 Base metal thickness range (SMAW).

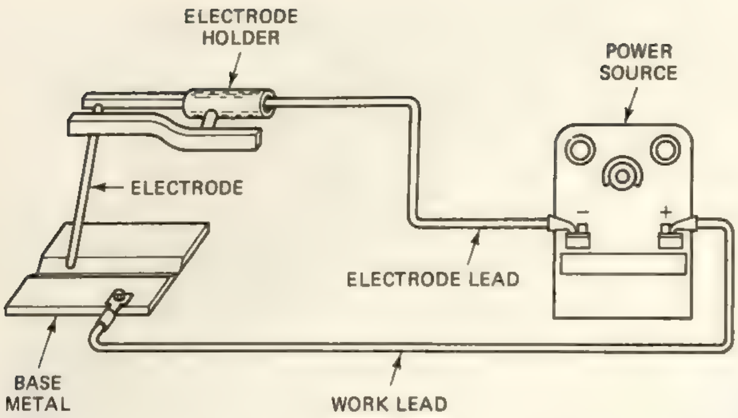


FIGURE 6-32 Circuit diagram (SMA

Welding can be accomplished with either alternating current (ac) or direct-current electrode negative (DCEN), straight polarity, or electrode positive (DCEP) reverse polarity.

Equipment Required to Operate

The welding machine or power source is the heart of the shielded metal arc welding system. Its primary purpose is to provide electric power of the proper current and voltage to maintain a controllable and stable welding arc.

The output characteristics of the power source must be of the constant-current (CC) type. The normal current range is from 25 to 500 A using conventional-size electrodes. The arc voltage varies from 15 to 35 V. Power sources for welding are covered in Chapter 10.

The next important piece of apparatus is the electrode holder, which is held by the welder. The holder firmly grips the electrode and transmits the welding current to it. Electrode holders come in several designs, which include the pincher type and the collet or twist type (Figure 6-33). Each style has its proponents and the selection is largely personal preference. Electrode holders are designated for their current-carrying capacity. The basis for selection is shown in Figure 6-34, which shows the current rating, duty cycle, maximum electrode size, and the cable size that is to be used. A nominal weight range is also provided. There are no standards or specifications for electrode holders in the United States; however, several European countries have specifica   s for electrode holders. The holders range from 8   14 in. long based on the rating. The weights shown a   ithout the cable. All electrode holders should be full   ulated. It is desirable to select the lightest-weight h   r that will accommodate the required electrode size   e used.

Electrode holders deteriorate rapidl   e they are so close to the arc and exposed to high heat   s extremely important to maintain electrode holde   that they retain their current-carrying efficiency and t   r insulating

FIGURE 6-33 SMAW electrode holders.

FIGURE 6-34 Size and capacity of electrode holders.

Electrode Holder Classification	Rating: Max Current amp	Rating: Duty Cycle %	Electrode Size–Max in.	Cable Size Maximum A.W.G.	Nominal Weight oz
Small	100	50	1/8	1	10 to 12
	200	50	5/32	1/0	10 to 14
Medium	300	60	7/32	2/0	12 to 20
Large	400	60	1/4	3/0	16 to 26
Extra	500	75	5/16	4/0	22 to 30
Large	600	75	3/8	4/0	28 to 36

qualities. Manufacturers supply spare parts so that the holders can be rebuilt and maintained for peak performance.

There are certain items of auxiliary equipment that can be used with the shielded metal arc process. These include low-voltage control circuits which provide for a cutoff of open-circuit voltage until the electrode is touched to the work. Other items include secondary contactors, remote control switches for the contactors, remote control current-adjustment devices, crater-eliminating devices, engine-idling devices for engine-driven machines, and so on.

Materials Used

The covered electrode is the only item of material normally required. The selection of the covered electrode for specific work is based on the electrode usability and the composition and properties of the deposited weld metal. In order to properly select an electrode it is well to understand the function of the coating, the basis of specifying, the usability factors, and the deposited weld metal properties.

The coating on the electrode provides (1) gas from the decomposition of certain ingredients of the coating to shield the arc from the atmosphere, (2) the deoxidizers for scavenging and purifying the deposited weld metal, (3) slag formers to protect the deposited weld metal with a slag from atmospheric oxidation, (4) ionizing elements to make the arc more stable and to operate with alternating current, (5) alloying elements to provide special characteristics to the deposited weld metal, and (6) iron powder to improve productivity of the electrode. Before the late 1920s, bare or lightly-coated electrodes were used for welding. However, since they were more difficult to use and did not produce high-quality weld metal they are no longer used.

Welding electrodes have been divided into various categories based on composition. More information about electrodes—manufacturing, specifications, selection, storage, and so on—is given in Chapter 13.

The American Welding Society has established a system for identifying and specifying the different types of electrodes and filler metals[11,12] (Figure 6-35). The mild steel and low-alloy steel-covered electrodes are prefixed by the letter E, followed by a four- or five-digit number. The prefix E means "electrode." The first two (or three) digits indicate the tensile strength in thousand pounds per square inch of the deposited weld metal. The third or fourth digit indicates the position for which the electrode is designed. No. 1 means "all positions," flat, horizontal, vertical, and overhead, and No. 2 means horizontal fillet and flat position only. No. 4 means vertical with downward progression. The fourth or fifth digit is a "usability" rating which indicates the type of coating, which in turn indicates the type of welding current that

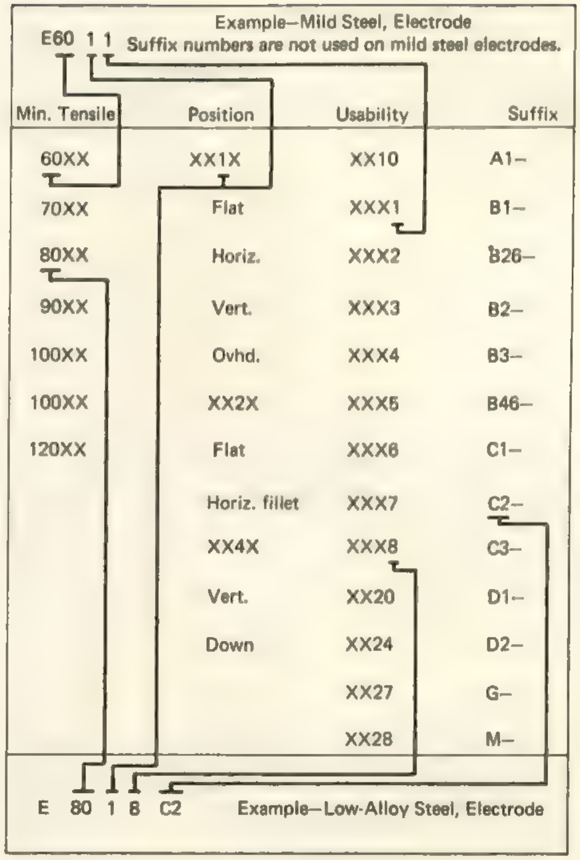


FIGURE 6-35 Covered electrode identification system.

is to be used. The exact meaning of each code number is given in Figure 6-36. Note that when the fourth or fifth digit is zero, the type of coating and current to use are determined by the third digit. For example, E6010 indicates a cellulose sodium coating and operates on dc electrode positive, while an E7018 has an iron powder low-hydrogen coating and operates on dc electrode positive or on ac. To identify electrodes, each is type marked or printed with the identifying number (Figure 6-37). Color coding was formerly used for identification but is no longer popular. The color coding is still used for surfacing electrodes.

The mechanical properties of the deposited weld metal must equal or exceed those of the base metal. Weld metal must also have approximately the same composition and physical properties.

The base metal must be identified so that its mechanical properties and composition are known. If the base metal is mild steel, select any E60XX electrode because its deposited metal will overmatch mechanical properties.

The abridged specifications for carbon steel-covered arc welding electrodes is shown in Figure 6-38. This provides the AWS classification, the radiographic standard, the mechanical properties, and also the

First Two or Three Digits Indicates Tensile Strength and Other Mechanical Properties					
AWS Classification[a]	Tensile Strength, Min.		Yield Strength, Min.		Elongation Min. (%)
	Ksi	MPa	Ksi	MPa	
E60XX					17
E70XX	70	450	57	390	22 & 25
E80XX	80	550	67	460	16 & 19 & 24
E90XX	90	620	77	530	14 & 17 & 24
E100XX	100	690	87	600	13 & 16 & 20
E110XX (1)	110	760	97	670	15 & 20
E120XX (1)	120	830	107	740	14 & 18

[a]110XX and 120XX refer to the low-hydrogen type of coating only.

Third (or) Fourth Digit Indicates the Welding Position That Can Be Used				
Classification	Flat Post. (F)	Horiz. Post. (H)	Vertical Post. (V)	Overhead Post. (OH)
EXX1X	Yes	Yes	Yes	Yes
EXX2X	Yes	Fillet	No	No
EXX4X	Yes	Yes	Down	Yes

Last Digit Indicates Usability of the Electrode						
Classification						Approximate Iron Powder[a]
ASME	AWS	Current	Arc	Penetration	Covering and Slag	
F-3	EXX10	DCEP	Digging	Deep	Cellulose–sodium	0–10%
F-3	EXXX1	AC and DCEP	Digging	Deep	Cellulose–potassium	0
F-2	EXXX2	AC and DCEN	Medium	Medium	Rutile–sodium	0–10%
F-2	EXXX3	AC and DC	Light	Light	Rutile–potassium	0–10%
F-2	EXXX4	AC and DC	Light	Light	Rutile–iron powder	25–40%
F-4	EXXX5	DCEP	Medium	Medium	Low hydrogen–sodium	0
F-4	EXXX6	AC or DCEP	Medium	Medium	Low hydrogen–potassium	0
F-4	EXXX8	AC or DCEP	Medium	Medium	Low hydrogen–iron powder	25–40%
F-1	EXX20	AC or DC	Medium	Medium	Iron oxide–sodium	0
F-1	EXX24	AC or DC	Light	Light	Rutile–iron powder	50%
F-1	EXX27	AC or DC	Medium	Medium	Iron oxide–iron powder	50%
F-1	EXX28	AC or DCEP	Medium	Medium	Low hydrogen–iron powder	50%

[a]Iron powder percentage based on weight of the covering.

FIGURE 6-36 Details of the classification system for mild and low-alloy steel electrodes.

FIGURE 6-37 Printed type marking on electrodes.

AWS Classification	Tensile Strength, Min. Ksi	MPa	Yield Strength at 0.2% Offset, Min. Ksi	MPa	Elongation Min. (%)	Radiographic Standard AWS Grade	V Notch Impact Min.[a] (ft-lb)
E6010	62	430	50	340	22	2	20 @ −20°F
E6011	62	430	50	340	22	2	20 @ −20°F
E6012	67	460	55	380	17	Not required	Not required
E6013	67	460	55	380	17	2	Not required
E6020	62	430	50	340	2	1	Not required
E6022	67	460	Not required		Not required	Not required	Not required
E6027	62	430	50	340	2	2	20 @ −20°F
E7014	72	500	60	420	17	2	Not required
E7015	72	500	60	420	22	1	20 @ −20°F
E7016	72	500	60	420	22	1	20 @ −20°F
E7018	72	500	60	420	22	1	20 @ −20°F
E7024	72	500	60	420	17	2	Not required
E7027	72	500	60	420	22	2	20 @ −20°F
E7028	72	500	60	420	22	2	20 @ −20°F
E7048	72	500	60	420	22	1	20 @ −20°F

[a]20 ft-lb at −20°F = 27 joule at −29°C and 20 ft-lb at 0°F = 27 joule at −18°C.

FIGURE 6-38 Abridged specifications for mild steel covered electrodes.

minimum V-notch impact requirements for the E60XX and E70XX class of electrodes. The radiographic standard is related to the allowable porosity limits as shown by the specification. The mechanical properties are the minimum tensile strength in thousand pounds per square inch or MPa, the minimum yield point in thousand pounds per square inch and the minimun elongation in 2 in. in percent. The V-notch impact requirements are a minimum at two temperatures, either 0 °F (−18 °C) or −20 °F (−29 °C). There are other requirements in this specification, and for this reason the specification itself must be referred to for details. Agreement between supplier and purchaser can utilize other impact requirements.

Welding Position Electrodes are designed to be used in specific positions. The third (or fourth) digit of the electrode classification indicates the welding position that can be used. Match the electrode to the welding position to be encountered.

Welding Current Some electrodes are designed to operate best with direct current (dc), and others operate best with alternating current (ac). Some will operate on either. The last two digits together indicate welding current usability. Select the electrode to match the type of power source to be used.

Joint Design and Fitup Welding electrodes are designed with a digging, medium, or soft arc for deep, medium, or light penetration. The last two digits of the classification taken together also indicate this factor. Deep penetrating electrodes with a digging arc should be used when edges are not beveled or fitup is tight, but light penetrating electrodes with a soft arc are required when welding on thin material or when root openings are too wide.

Service Conditions or Specifications For weldments subject to severe service conditions, such as low temperature, high temperature, or shock loading, select the electrode that matches base metal composition, ductility and impact resistance properties. The low-hydrogen types should be used.

Production Efficiency and Job Conditions Some electrodes are designed for high deposition rates but may be used only under specific position requirements. If they can be used, select the high-iron-powder types—EXX24, 27, 28 or 48. Other conditions may be present which will require experimentation to determine the most efficient electrode.

For the usability of covered electrodes the mild steel electrodes are classified into four general groups.

- □ *F-1, High-deposition group:* iron powder types
- □ *F-2, Mild penetration group:* rutile (titania) types
- □ *F-3, Deep penetration group:* high-cellulose types
- □ *F-4, Low hydrogen group:* lime types

Figure 6-39 is a guide to aid in selecting the covered electrode for specific welding jobs based on the welding position, metal thickness, and weld type.

Electrodes in the same grouping operate and are run the same way. These F numbers correspond to the classification system used in Section IX of the ASME Pressure Vessel Boiler Code.

Deposition Rates

The melting rate of the electrode is related to the welding current. A portion of the arc energy is used to melt the surface of the base metal and part to melt the electrode.

Welding Position ↓ \ Weld Type →	Fillet Welds: Inside or Outside				Groove Welds: Square		Vee (Open Root)		U	
Material Thickness →	Very Thin	Thin	Medium	Thick	Very Thin	Thin	Medium	Thick	Medium	Thick
1 FLAT	F 2	F 2	F 1	F 1 F 4	F 2	F 3	F 3	F 3 F 4	F 4	F 4
1A HORIZ FILLET	F-2	F-3	F-1	F 1 F 4	—	—	—	—	—	—
2 HORIZ	F-2	F 3	F 3 F 4	F-3 F 4	F 2	F 2 or F 3	F-3 and F-4	F 3 F-4	F 4	F 4
3 VERT UP	F 2	F 3	F 4	F-4	F 2	F-2 or F-3	F-3 and F 4	F 3 and F 4	F 4	F 4
3A VERT DOWN	F 2	F 3	—	—	F 2	F-2 or F 3	F 3	F 3	F 3	F 3
4 OVER HEAD	F 2	F-3	F-3 F 4	F 3 F-4	F 2	F-2 or F-3	F-3 and F-4	F-3 and F-4	F-4	F-4
5 PIPE FIXED DOWNHILL	—	—	—	—	F-2	F-2	F-3	F-3	F 3	F-3
5A PIPE FIXED UPHILL	—	—	—	—	F 3	F-3	F-3 and F 4	F-3 and F 4	F 4	F 4

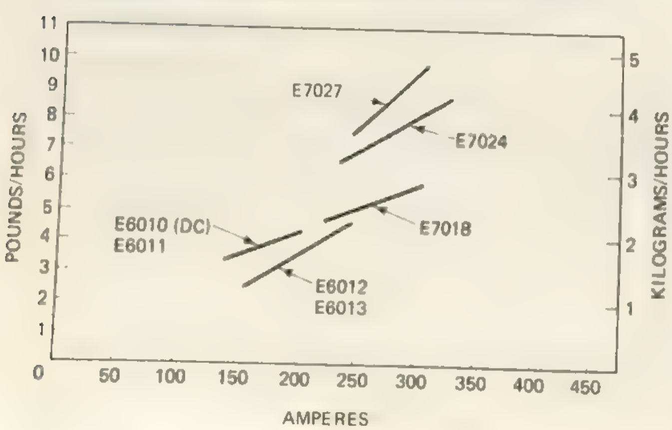
Material Thickness: Very thin = .005" to .063" (.125–1.6 mm),
Thin = $\frac{1}{16}$"–$\frac{1}{4}$" (1.6–6.3 mm), Medium = $\frac{1}{4}$"–$\frac{3}{4}$" (6.3–19 mm),
Thickness = $\frac{3}{4}$"-up (19 mm-up)

FIGURE 6-39 Usability rating guide for selecting mild style and low-alloy electrodes.

The electrode coating also affects deposition rates. The iron oxide types and iron powder types have higher deposition rates.

The melting rate to current is a fairly direct relationship (Figure 6-40). With higher current, the current density in the electrode increases and this increases the melting rate which increases the deposition rate. Electrode size is determined by the job, the welding position, the joint detail, and the skill of the welder.

FIGURE 6-40 Deposition rates for various electrodes.



Quality of Welds

The quality of the weld depends on the design of the joint, the electrode, the technique, and the skill of the welder. If joint details are varied greatly from established design details, lower quality can result. The fitup of joints must match the design. Some electrodes deposit higher-quality weld metal than others, based on their specifications.

Weld Schedules

Welding schedules are tables of operating parameters that will provide high-quality welds under normal conditions. Strict welding schedules are not as important for manual shielded metal arc welding as for semiautomatic and automatic welding for several reasons. First, in manual welding the welder controls welding conditions more by the manipulation of the arc than in any of the other arc welding processes. The welder directly controls the arc voltage and travel speed and indirectly the welding current. Second, in shielded metal arc welding, meter

readings are rarely used for the duplication of jobs. It is felt that recommended welding conditions for the different types of electrodes are sufficient for most operations (Figure 6-41). However, when more complete information is needed see the data provided by Figure 6-42. The settings given in these tables provide a good starting point when first welding on a new application. They are not necessarily the only welding settings that can be used under every condition. For example, for high-production work, the current settings could be increased considerably over those shown. Such factors as weld appearance, welder skill, and quality level will allow variations from the settings. As the requirements of a new application become better known the settings can be adjusted to ob- optimum welding conditions. Trials are required prior to the establishment of a firm procedure for specific applications.

These tables are based on welding low carbon mild under normal conditions and show the suggested electrode types for different weld types. Other electrode s and joints may be used. They are made in a consistent manner and are based on the type of welds and the position of welding, and are made by a welder of normal skill.

Tips for Using the Process

There is a definite relationship between the welding current, the size of the welding electrodes, and the welding position. These must be selected so that the welder has the molten weld metal pool under complete control at all times. If the pool becomes too large, it becomes unmanageable and molten metal may run out of the pool, particularly in out-of-position welding.

The welder should maintain the steady frying and crackling sound that comes with correct procedures. The shape of the molten pool and the movement of the metal at the rear of the pool serve as a guide in checking weld quality. The ripples produced on the bead should be uniform and the bead should be smooth with no overlap or undercut. The following seven factors are essential for maintaining high-quality welding.

1. *Correct electrode type.* It is important to select the proper electrode for each job. This should be based on information presented in the earlier part of this section.
2. *Correct electrode size.* Electrode size choice involves consideration of the type of electrode, welding position, joint preparation, weld size, welding current, the thickness or mass of the base metal, and the skill of the welder.
3. *Correct current.* If the current is too high, the electrode melts too fast and the molten pool is large and irregular and hard to control. If the current is too low there is not enough heat to melt the base metal and the molten pool will be too small and will pile up and be irregular (Figure 6-43a).
4. *Correct arc length.* If the arc is too long, the metal melts off the electrode in large globules which wobble from side to side giving a wide, spattered, and irregular bead with poor fusion to the base metal. It may also result in porosity, especially with low-hydrogen electrodes. If the arc is too short, there is not sufficient heat in the arc at the start to melt the base metal sufficiently and the electrode often sticks to the work.

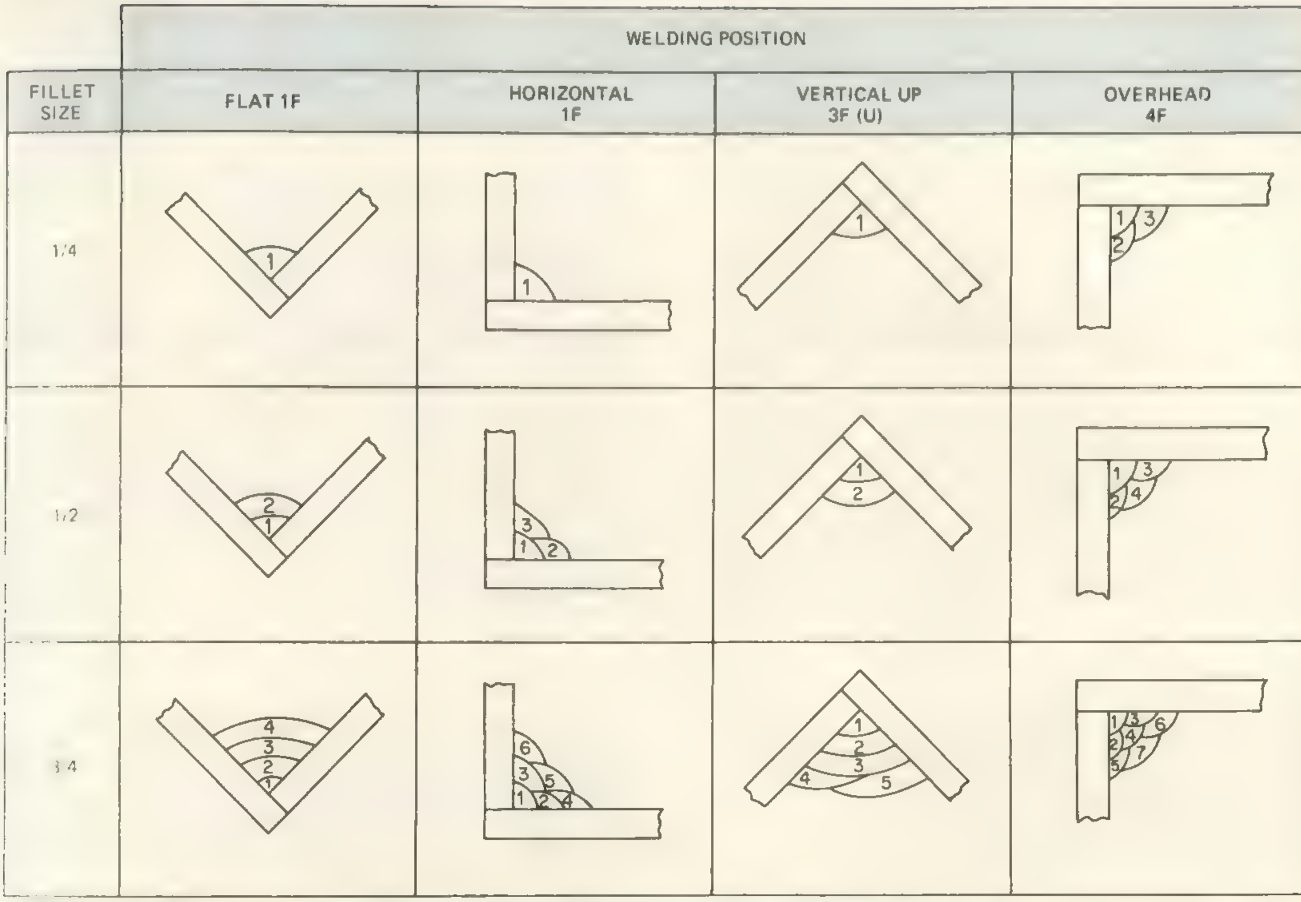
FIGURE 6-41 Recommended welding conditions for covered electrodes.

Type of Electrode	Size mm	Size inch	Direct Current amps	Direct Current volts	Alternating Current amps	Alternating Current volts
E-6010 F-3	2.38	3/32 × 14	40-80	24-26		
All position	3.18	1/8 × 14	70-130	24-26		
Deep penetration	3.97	5/32 × 14	110-165	21-23	—	—
DC EP	4.76	3/16 × 14	140-225	20-26		
	5.56	7/32 × 18	160-300	20-32		
	6.35	1/4 × 18	200-400	24-34		
E-6011 F-3	2.38	3/32 × 14	50-70	21-26	50-70	26-29
All position	3.18	1/8 × 14	75-130	20-30	75-130	26-28
Deep penetration	3.97	5/32 × 14	120-160	16-26	120-160	24-29
AC or DC EP	4.76	3/16 × 14	150-190	20-28	150-190	24-33
	5.56	7/32 × 18	180-250		180-250	
	6.35	1/4 × 18	200-300	22-28	200-300	30-40
E-6012 F-2	2.38	3/32 × 14	50-90	16-26	80-120	
All position	3.18	1/8 × 14	75-135	16-22	80-120	17-23
Medium penetration	3.97	5/32 × 14	120-205	16-24	120-190	17-26
AC or DC EN	4.76	3/16 × 14	140-255	17-26	140-240	17-28
	5.56	7/32 × 18	220-335	12-28		
	6.35	1/4 × 18	200-400	16-25		

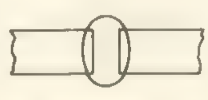
Type of Electrode	Size		Direct Current		Alternating Current	
	mm	inch	amps	volts	amps	volts
E-6013 F-2	2.38	3/32 X 14	50-100	21-24	50-80	20-27
All position	3.18	1/8 X 14	80-140	18-20	80-120	22-24
Light penetration	3.97	5/32 X 14	120-190	20-25	120-170	22-26
AC or DC	4.76	3/16 X 14	160-220	25-28	190-220	20-22
	5.56	7/32 X 18	240-270			
	6.35	1/4 X 18	270-350	18-21	270-350	20-22
	7.94	5/16 X 18	320-420	23-26	320-420	24-30
E-6020 F-1	2.38	1/8 X 14	120-145	20-22	120-145	20-22
Flat and HF position	3.18	5/32 X 14	150-175	24-26	150-175	24-26
Medium penetration	3.97	3/16 X 18	210-240	23-27	210-240	23-27
High deposit rate	4.76	7/32 X 18	240-275	24-28	240-275	24-28
AC or DC	5.56	1/4 X 18	290-320	29-30	290-320	29-30
E-7010			Same as E6010 above			
E-7014 F-2	2.38	3/32 X 14	70-90	20-24	70-90	20-24
All position	3.18	1/8 X 14	120-145	14-17	120-145	14-17
Light penetration	3.97	5/32 X 14	140-250	17-19	140-210	17-19
AC or DC	4.76	3/16 X 18	180-280	20-24	180-280	20-24
	5.56	7/32 X 18	250-375	28-35	250-375	28-35
	6.35	1/4 X 18	300-420	26-31	300-420	26-31
	7.94	5/16 X 18	375-500	28-33	375-500	28-33
E-7016 F-4	2.38	3/32 X 14	70-100	17-21	70-100	20-25
All position	3.18	1/8 X 14	80-130	17-22	40-130	20-22
Medium penetration	3.97	5/32 X 14	120-170	18-19	120-170	18-20
AC or DC EP	4.76	3/16 X 14-18	170-250	17-22	170-250	17-23
	5.56	7/32 X 18	250-325			
	6.35	1/4 X 18	300-350	21-25	300-350	19-22
	7.94	5/16 X 18				
E-7018 F-4	2.38	3/32 X 14	80-110	20-22	80-110	24-26
All position	3.18	1/8 X 14	90-150	20-21	90-150	19-23
Medium penetration	3.97	5/32 X 14	110-230	20-22	110-230	20-25
AC or DC EP	4.76	3/16 X 14	150-300	20-22	150-300	21-28
	5.56	7/32 X 18	250-350	20-24	250-350	20-29
	6.35	1/4 X 18	300-400	20-24	300-400	24-30
	7.94	5/16 X 18				
E-7024 F-1	2.38	3/32 X 12	100-140	27-32	100-140	27-32
Flat and HF position	3.18	1/8 X 14	130-180	27-30	130-180	27-30
Light penetration	3.97	5/32 X 14	180-240	30-33	180-240	30-33
High deposition rate	4.76	3/16 X 14	200-280	22-28	200-280	22-28
AC or DC	5.56	7/32 X 18	250-375	29-32	250-375	29-32
	6.35	1/4 X 18	300-420	28-34	300-420	28-34
	7.94	5/16 X 18	425-500	29-35	425-500	29-35
E-7028 F-1	2.38	1/8 X 14	–	–	–	–
Flat and HF position	3.18	5/32 X 14	–	–	–	–
Medium penetration	3.97	3/16 X	240-300	31-33	260-320	30-33
High deposition rate	4.76	7/32 X 18	300-400	36-40	320-400	30-35
AC or DC EP	5.56	1/4 X 18	350-450	37-41	370-470	31-37
	7.94	5/16 X 18				
E-8018			Same as E7018 above			

Note: Voltage is based on a normal arc length measured at the arc.

FIGURE 6-41 (*cont.*)



WELDING POSITION	SUGGESTED ELECTRODE TYPE	ELECTRODE DIAMETER FOR MATERIAL THICKNESS INCH		
		1/4	1/2	3/4
1F, 2F	E7024	1/4	1/4	1/4
3F (U)	E7018	5/32	5/32	5/32
4F	E6010	3/16	3/16	3/16
	E7018	5/32	5/32	5/32

MATERIAL THICKNESS (IN.)	WELDING POSITION
1/8	ALL POSITIONS
3/16	
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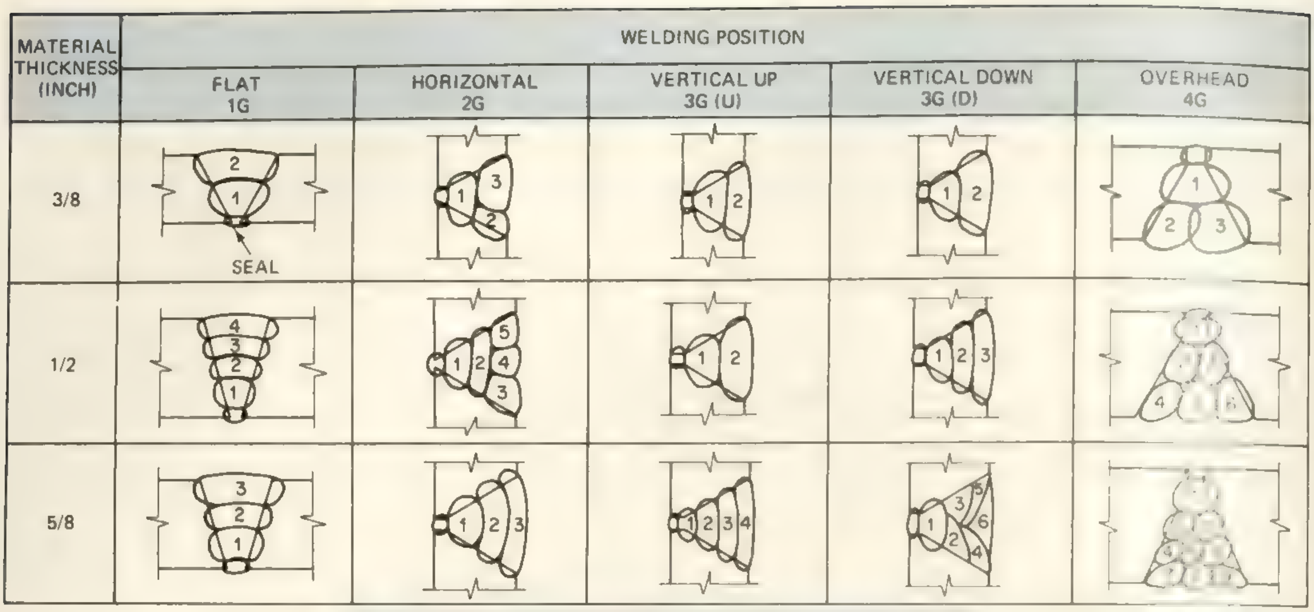
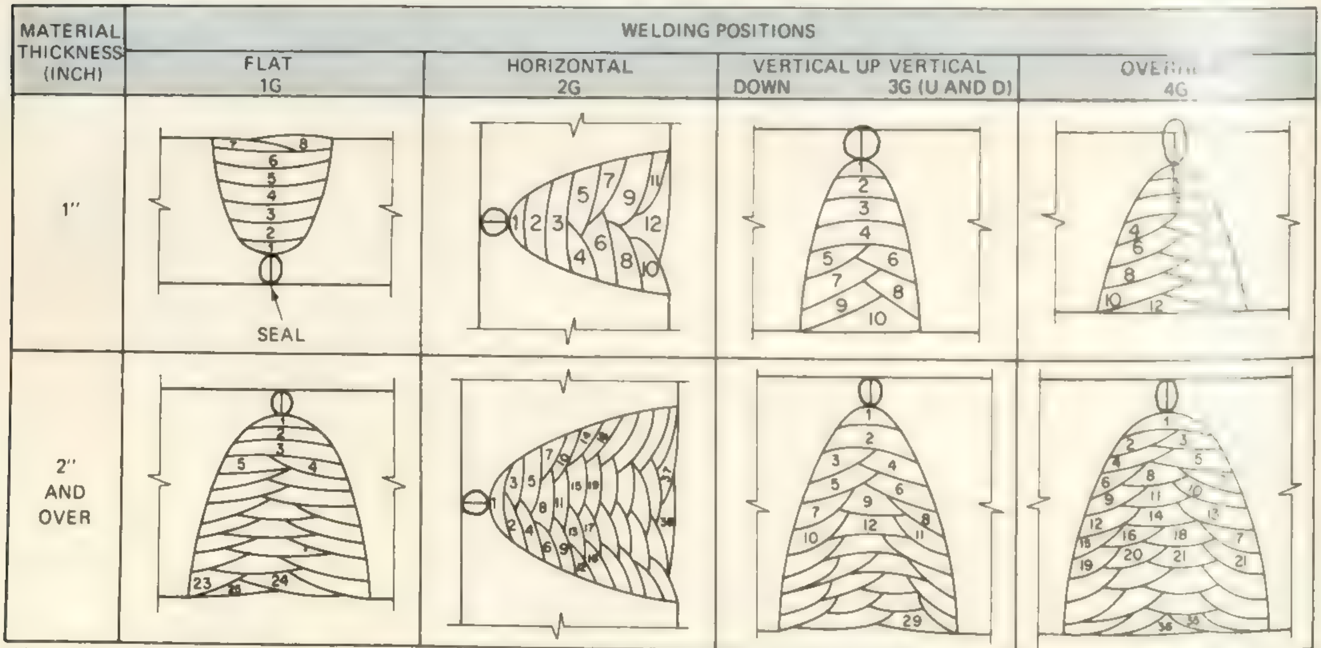
WELDING POSITION	SUGGESTED ELECTRODE TYPE	ELECTRODE DIAMETER FOR MATERIAL THICKNESS (IN.)		
		1/8	3/16	1/4
1G	E6010	3/32	1/8	5/32
2G, 3G(U)	E6010, E6012			
3G(D), 4G	E6014, E6013	3/32	1/8	5/32

FIGURE 6-42 **Welding procedure schedule.**



WELDING POSITION	SUGGESTED ELECTRODE TYPE	ELECTRODE DIAMETER FOR MATERIAL THICKNESS (IN.)		
		3/8	1/2	5/8
1G	E6010	3/16	3/16	3/16
2G	E6010	3/16	3/16	3/16
	E7018	5/32	5/32	5/32
3G (U)	E6010	5/32	5/32	5/32
3G (D), 4G	E7018	5/32	5/32	5/32



NOTE. SEAL PASS SHOULD BE E6010, 5/32 OR 3/16" DIAMETER.

WELDING POSITION	SUGGESTED ELECTRODE TYPE	ELECTRODE DIAMETER FOR MATERIAL THICKNESS (IN.)	
		1	2
1G	E7018	1/4	1/4
2G	E7018	5/32	5/32
3G (U)	E6010	3/16	3/16
3G (D), 4G	E7018	5/32	5/32

FIGURE 6-42 *(cont.)*

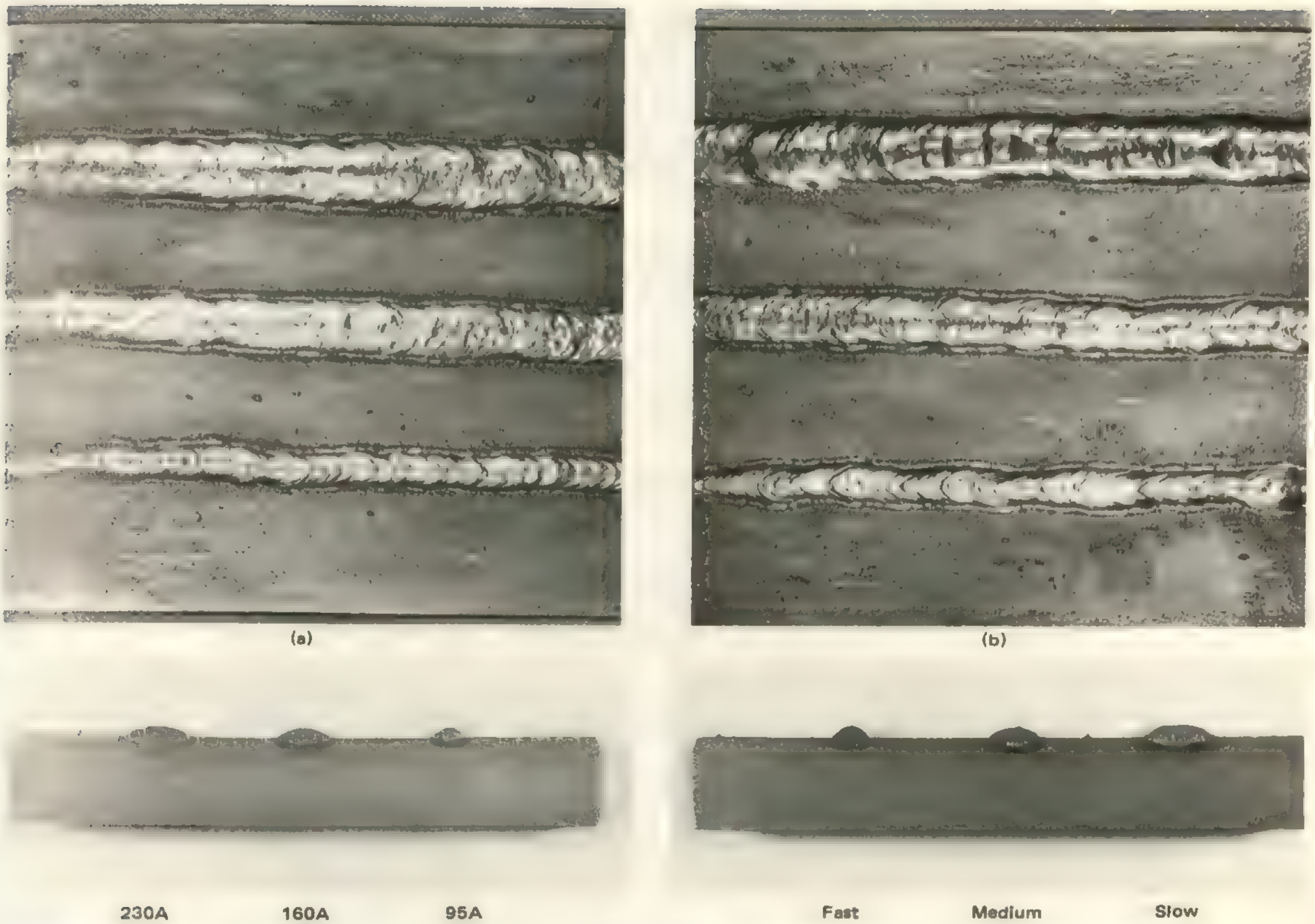


FIGURE 6-43 Welding variable travel speed and current using E7024 covered electrode: (a) constant travel speed, changing current; (b) all beads 160 A, changing travel speed.

5. *Correct travel speed.* When the speed is too fast, the weld pool freezes too quickly. Impurities and gases are not allowed to be released. The bead is narrow and the ripples pointed. When the speed is too slow the metal piles up, the bead is too high and wide with a rather straight ripple (Figure 6-43b). The factors: correct current, correct arc length (or voltage) and correct travel speed all relate to heat input. An experienced welder inherently adjusts these factors for the optimum weld under every possible condition. By referring to Figure 6-44 the welder in training can learn to adjust these factors for the best possible weld.
6. *Correct electrode angle.* The electrode angle is important, particularly in fillet welding and in deep groove welding. Generally, when making a fillet the electrode should be held so that it bisects the angle between the plates and is perpendicular to the line of the weld. When undercut occurs in the vertical member, lower the angle and direct the arc toward the vertical member.
7. *Correct manipulation pattern.* Different manipulation patterns are used for different types of electrodes, different weld designs, and different welding positions. Knowledge of the different patterns is learned in a good welding training program.

Breaking the Arc In breaking the arc it is important to know whether it will be immediately reestablished with the next electrode and continued or whether it is the end of a weld. If the weld is to be continued, the crater should remain, and the arc should be quickly broken. If it is the end of the weld, the arc should not be broken until travel has stopped momentarily to allow the crater to fill.

When weaving is used, the width of the weave and the pause at the end of the weave and other movements become important. The welder must pause at each end of the weave to allow for complete fusion into the side. The welder should quickly move across the center of the weld since heating is more concentrated in the center than at the edges. The width of the weave for low-hydrogen electrodes should not exceed two and one-half times the

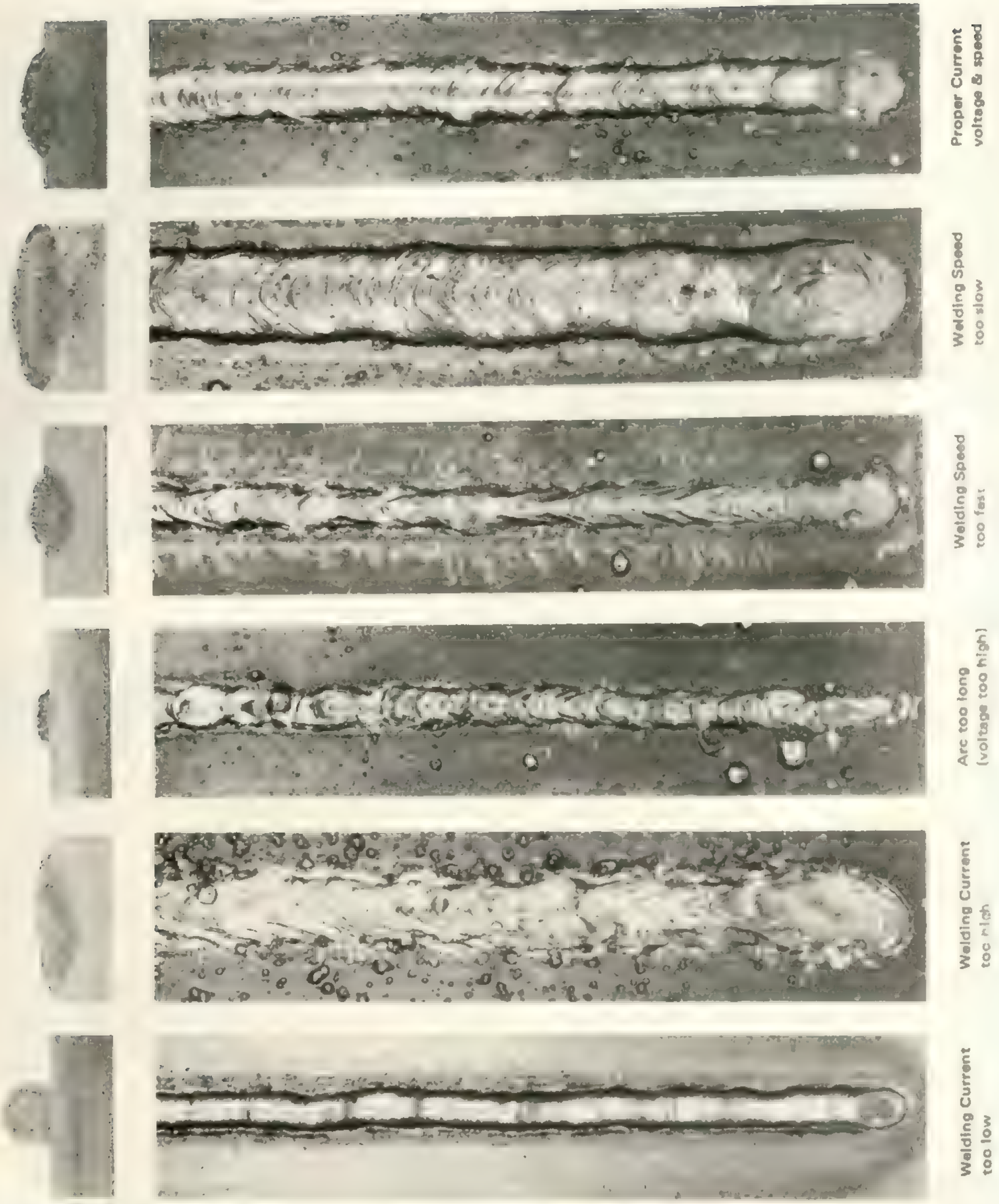


FIGURE 6-44 Welding examples relating to malpractices.

core wire diameter. For other electrode types, this can be doubled.

Safety Considerations

The safety factors and potential hazards involved with the shielded metal arc process are discussed in detail in Chapter 3.

Limitations of the Process

One of the major limitations to the shielded metal arc process is the "built-in break." Whenever an electrode is consumed to within 2 in. (50 mm) of its original length, the welder must stop. Welding cannot continue since the bare portion of the electrode in the electrode holder should not be used. The welder must stop, chip slag,

remove the electrode stub, and place a new electrode in the holder. This occurs many times during the workday and is controlled by the size and length of the electrode. This prohibits the welder from attaining an operator factor or duty cycle much greater than 25%.

Another limitation is the filler metal utilization. The electrode stub loss and the coating loss allows for a total utilization of covered electrode of approximately 65%.

Variations of the Process

The variations of the shielded metal arc welding process are:

- Gravity welding
- Fire cracker welding
- Massive electrode welding
- Arc spot welding

Gravity Welding Gravityfeed welding, which utilizes heavy-coated electrodes, was first described in 1938 by K. K. Madsen of Denmark.[13] Gravity welding is considered an automatic method of applying the shielded metal arc welding process. It utilizes a low-cost mechanism that includes an electrode holder attached to a bracket which slides down an inclined bar arranged along the line of the weld. Heavy-coated electrodes are maintained in contact with the workpiece by the weight of the electrode holder bracket and the electrode. Once the process is started, it continues automatically until the electrode is consumed. When the electrode has burned to a short stub the bracket and electrode holder are automatically kicked up to break the arc.

This welding method received considerable publicity in the early 1960s, based on work done in Japanese shipyards. Equipment for gravity welding was made during the 1940s in the Scandinavian countries, in England, in Japan, and in the United States. An inclined arm automatic stick feeder was available in the late 1940s in the United States. A *contact-er* electrode holder was developed in the United States to utilize contact-type electrodes in approximately 1950. Credit should be given to the Japanese shipbuilders for perfecting and utilizing the gravity welding system on a large scale. The gravity system is being used in shipyards throughout the world. It is also used in railroad car shops, barge yards, and other applications in which a large amount of horizontal fillet welds are to be made within a relatively small area.

The gravity welding system provides welding economies over manual welding since the operator can use a number of the gravity feeders simultaneously. This increases the productivity of the welders, reduces welder fatigue, operator training is minimized, and there is a substantial savings in welding labor cost. Initially, electrodes of standard length 18 in. (550 mm) were used; however, the Japanese designed extra-long electrodes to make the process more productive. The most common length is now 28 in. (800 mm). This reduces the stub end loss ratio over that of normal length electrodes.

Special electrode feeders are required to utilize gravity welding. There are two types of feeders in common use: one is the tripod or gravity feeder, which has an electrode holder mounted on a bracket or carriage that slides down an incline (Figure 6-45). It is used to produce horizontal fillet welds. The second type is a spring-loaded holder, used for making flat-position groove welds, as well as horizontal fillet welds (Figure 6-46). The tripod type of feeder is the most popular since it provides a more uniform weld throughout its entire length. On the other hand, the spring-loaded feeder has the advantage of being usable in less accessible spaces.

The power source for gravity welding is a conventional constant current welding machine used for manual shielded metal arc welding. The current rating and duty cycle of the machine must be considered, since gravity welding can attain a 90% duty cycle. Currents of up to 400 A can be used based on the electrode type and size. The conventional 60% duty cycle welding power source must be derated to allow for the 90% duty cycle. Both alternating-current and direct-current power sources are used.

Heavy-coated welding electrodes must be used for gravity welding. The E6027 type and the E7024 type are most often used; however, the E7028 type can also be used. The most common size electrodes used are the $\frac{7}{32}$-in. (5.6-mm) and the $\frac{1}{4}$-in. (6.4-mm) diameters. The most commonly used length is 28 in. (800 mm); however, other lengths can be used. Shorter electrodes do not provide the economies and longer electrodes are somewhat flexible and not as efficient as the 28 in. length. The size and length of fillet welds produced by these electrodes can be varied with the gravity feeders based on changing the angle of the inclined track. It is possible to obtain welds from 20 to 40 in. (500 to 1000 mm) long with the 28-in electrode, depending on the adjustment of the feeder. Horizontal fillet welds with a leg length of from $\frac{7}{32}$ in. (5.6 mm) to $\frac{3}{8}$ in. (9.5 mm) can be obtained. The properties of the weld metal deposited when using the gravity feed system are the same as when electrodes are used manually. Welding procedures are slightly different for the different types and makes of gravity feeders.

There are two variations of the tripod gravity feeder. One is preset and allows for no adjustment of the incline of the track, whereas the other type allows the tripod legs to be adjusted. The preset feeder will produce welds in lengths that vary from approximately 27 to 31 in. (675 to 775 mm) long, using the 28-in. (800-mm) electrode. Figure 6-47 shows the welding procedure when using the preset type of gravity feeder. With two different sizes of electrodes available, two different sizes of fillet welds can be obtained. Normally, to fulfill the requirements of a particular weldment design, a specific fillet

FIGURE 6-45 Gravity feeders used for shipbuilding.

FIGURE 6-46 Spring-loaded feeder.

size is specified. The electrode type and size must be selected to fulfill this requirement. The welding current will determine the specific weld fillet size and weld length. Two different levels of current can be employed with the two different types of electrodes. The higher current will produce the larger fillet size. Some of the non-adjustable-type feeders have a base plate variation, which slightly changes the track angle and will increase the length of the resulting weld. It is important to relate the exact type of feeder to this table for consistent results.

The second variation of the tripod gravity feeder provides for leg-length adjustments. This provides a different angle of the inclined track. With this type of feeder a variety of fillet sizes can be produced with the same electrode size operating at the same welding current. The manufacturer's instructions provide information for leg-length adjustments. The fillet weld size is determined by the electrode diameter and by the weld-length setting used with the adjustable feeder. The weld length may be varied depending on angle adjustments which are established between the axis of the weld, the centerline of the electrode, and the inclined track of the gravity feeder. The actual

Feeder	Fillet Size inch	Electrode	Electrode Size inch	Weld Length inch	Weld Current
Preset Gravity Type (Fixed Legs)	9/32	E6026	7/32	27	260 AC
	11/32	E6027	1/4	27	290 AC
	1/4	E6027	7/32	31	260 AC
	5/16	E6027	1/4	31	290 AC
	9/32	E7024	7/32	27	290 AC
	11/32	E7024	1/4	27	350 AC
	1/4	E7024	7/32	31	290 AC
	5/16	E7024	1/4	31	350 AC
Spring Loaded Type	1/4	E6027	7/32	27	240 AC
	5/16	E6027	1/4	27	270 AC
	1/4	E7024	7/32	27	270 AC
	5/16	E7024	1/4	27	300 AC

FIGURE 6-47 Weld procedures for gravity welding.

range of weld sizes obtainable will depend on the specific feeder being used. For production work of the same size of fillet the preset or nonadjustable tripod feeder is preferred.

The spring-loaded feeder produces welds 24 to 27 in. (600 to 675 mm) long using a 28-in. (800-mm)-long electrode. A normal stub length of 2 in. (50 mm) results. The weld size is established by the electrode diameter. Figure 6-47 is a table that shows the fillet weld size and is related to the electrode size and welding current.

When using the spring-loaded feeders there is a small size variation of the fillet from the beginning of the weld to the end of the weld. There is also a change in penetration from start to end. This is due to the change in the approach angle that occurs during the melting of the electrode. There is also a variation in weld appearance and spatter levels, depending on whether the weld is progressing toward or away from the work lead connection.

When direct current is used the electrode is negative (straight polarity). When alternating current is used, the change in bead smoothness and spatter level is less dependent on welding direction related to the work lead connection.

The economic advantage of using gravity feeders depends on one welding operator utilizing two or more feeders simultaneously. It is the labor cost that is largely involved in using more than one feeder. When using long electrodes in gravity feeders, the welding current is less than normally used for manual welding with standard length electrodes. Because of this, it is necessary to use at least two gravity feeders to obtain an economic advantage. Additional cost reduction is possible by using three or four automatic feeders. The most economical operation is to have a sufficient number of feeders in a small area so that the operator can move from one to another and reload the holder and reestablish the arc of one feeder while all of the other feeders are welding. Figure 6-48 shows a comparison of the deposition rate based on

Method of Applying To Make 5/16" Fillet	Deposition Rate (E6027)
Manual-one arc	10 lb/hr
Gravity-two arcs	17 lb/hr
Gravity-three arcs	26 lb/hr
Gravity-four arcs	34 lb/hr
Gravity-five arcs	43 lb/hr

FIGURE 6-48 Comparison of deposition rates for gravity welding.

pounds per hour when using one electrode manually versus two, then three or four or five gravity feeders.

Gravity welding is an excellent method of applying shielded metal arc welding when a sufficient number of horizontal fillets are to be made in a concentrated area. Gravity welding is becoming less popular due to more widespread use of semiautomatic welding using flux-cored electrodes.

Firecracker Welding Firecracker welding is a shielded metal arc welding process variation that uses a length of covered electrode placed along the joint in contact with the workpiece. During welding the stationary electrode is consumed as the arc travels the length of the electrode. This method was developed by George Hafergut of the Elin Company of Austria and is known as the Elin-Hafergut welding method.[14] It was developed in the late 1930s and was used for bridge welding for making longitudinal seams in small tanks, and for making welds on railroad cars and bus bodies. It is considered an automatic method of application since human involvement is not required after the arc is initiated. It can be used for making square groove butt welds in materials from 0.030 in. (0.8 mm) to 0.120 in. (3 mm), for making full fillet lap welds in materials of similar thicknesses, and for making fillet welds from 3/16 in. (5 mm) and heavier. AWS types E6024 and E7028 can be used.

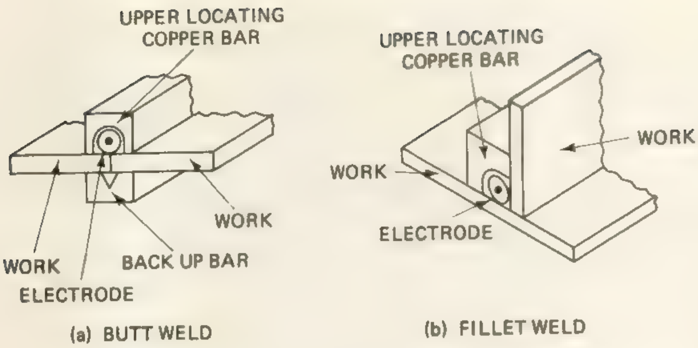


FIGURE 6-49 Firecracker welding.

To make a firecracker fillet weld the work is positioned so the weld is in the flat position. The welding electrode is placed in the joint and a retaining bar is placed over it. The arc is started by shorting the end of the electrode to the work. The arc length depends on the thickness of the coating. As the arc travels along the electrode, the electrode melts and makes a deposit on the material immediately underneath it. Once the arc is started, the process proceeds to completion automatically. Figure 6-49 shows the method being used for making butt welds and fillet welds. Electrodes up to 39 in. long (1000 mm) and with a 5-, 6-, 7-, or 8-mm core diameter have been used. Both alternating current and direct current have been used and there seems to be a preference for alternating current because of arc blow with direct current. The quality of the weld metal is equal to that produced by manual welding. One operator can make several firecracker welds simultaneously.

This method of shielded metal arc welding has been used very little in North America. The popularity of semiautomatic welding is responsible. However, for short repetitive welds firecracker welding should be considered.

Massive Electrode Welding There is another variation that employs extremely large diameter and long electrodes. These electrodes are made especially for repairing castings and are used at extremely high-current levels. These electrodes are so large and heavy that they require a manipulator to hold them and to feed them into the arc. Figure 6-50 is an example of these large electrodes being used for repairing a faulty casting. Size range and welding current required are shown in Figure 6-51. These electrodes are for very special applications, but for this particular requirement it is an excellent welding method.

Arc Spot Welding The shielded metal arc welding process can be used for arc spot welding. Special spring-loaded feeders are used with small-diameter electrodes for arc spot welding thin sheet metal. This method has its major use in the automotive body repair operations. Arc spot welding as a special welding application is discussed in detail in Chapter 26.

Industrial Use and Typical Applications

Typical applications of the shielded metal arc welding process are as varied and widespread as arc welding processes in general. Shielded metal arc welding will probably always be the mainstay for maintenance and repair welding; because welding is required at remote locations, the jobs are relatively small and each and every one is different. Shielded metal arc welding will also remain popular in small production shops where limited capital is available and where the amount of welding is relatively minor to other manufacturing operations.

FIGURE 6-50 Using massive electrodes.

Electrode Size (in.) Diameter Length	Current Range DCEP (A)	Approx. Puddle Size	Weld Metal Deposition Rate (lb/hr)
5/16 × 24	300–500	2–6	10
3/8 × 24	400–600	6–10	25
1/2 × 30	600–950	10–20	25
5/8 × 30	600–1500	20–36	45
3/4 × 36	1200–2100	36–60	60

FIGURE 6-51 Deposition rate chart for massive electrodes.

6-4 GAS METAL ARC WELDING

Gas metal arc welding (GMAW) is an arc metal welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of pressure. The welder's view of this arc is shown in Figure 6-52.

There are a number of variations of the gas metal arc welding process and the process has been given many different trade names. For example, variations are called MIG welding, CO_2 welding, fine wire welding, spray arc welding, pulsed arc welding, dip transfer welding, and short-circuit arc welding. These variations are of sufficient importance that each will be more clearly defined and explained.

Principles of Operation

The gas metal arc welding process (Figure 6-53) utilizes the heat of an arc between a continuously fed consumable electrode and the work to be welded. The heat of the arc melts the surface of the base metal and the end of the electrode. The metal melted off the electrode is transferred through the arc to the work where it becomes the deposited weld metal. Shielding is obtained from an envelope of gas, which may be an inert gas, an active gas, or a mixture. The shielding gas surrounds the arc area to protect it from contamination from the atmosphere. The electrode is fed into the arc automatically, usually from a coil. The arc is maintained automatically and travel and guidance can be manually or by machine.

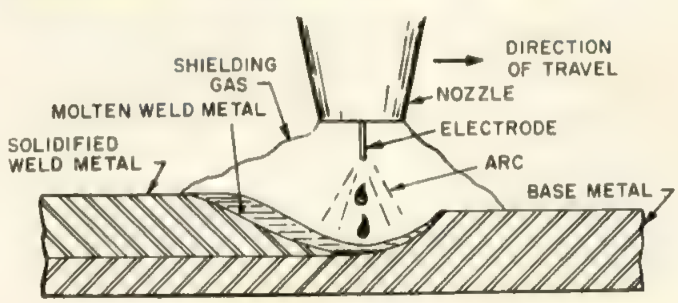
The metal being welded dictates the composition of the electrode and the shielding gas. The shielding gas and the type and size of the electrode affects the type of metal transfer. The metal transfer mode is one way of identifying the variations of the process.

Advantages and Major Uses

The gas metal arc welding process has become one of the most popular arc welding processes. Early development was for welding aluminum using inert gas for shielding—hence the name "metal inert gas" (MIG) welding. For welding steels inert gases were expensive and an active gas, CO_2, was selected. The selection of CO_2 was based on the analysis of gases formed by the disintegration of the coatings of covered electrodes. This variation, named CO_2 welding, was well adapted for welding mild steel in the flat position utilizing relatively large size [1/16 in. (1.6 mm)] electrode wires. This variation never became too popular with welders because of the high heat and necessity for high travel speeds. The metal transfer was globular and spatter was greater than desired. Efforts to

FIGURE 6-52 Welder's view of gas metal arc welding.

FIGURE 6-53 Process diagram (GMAW).



refine this variation led to an all-position capability still using CO_2 gas shielding but with smaller-diameter electrodes, on the order of 0.035 in. (0.9 mm) and 0.045 in. (1.1 mm) in diameter. This variation is called short-circuiting metal transfer or dip transfer welding. Efforts to improve weld appearance led to shielding gas mixtures of argon and CO_2, which provided a smoother, nicer-appearing weld surface.

Further development with different shielding gases led to the "spray arc" variation, which utilized larger-diameter electrodes, with a shielding gas mixture of 95% argon and 5% oxygen (other mixtures were 98:2 and 99:1 argon–oxygen mixtures). This gas mixture produced a spray-type metal transfer and welds with an extremely smooth surface. This variation has become extremely popular.

A later variation is pulsed arc welding, where the welding current is pulsed at regular intervals to create a discrete transfer of metal across the arc rather than a random transfer which occurs in the other variations.

The major advantages of gas metal arc welding are:

- High deposition rates when related to shielded metal arc welding
- High operator factor with respect to shielded metal arc welding
- High utilization of filler material
- Elimination of slag and flux removal
- Reduction of smoke and fumes
- May be automated for high-operator factor
- Skill level in the semiautomatic method of application slightly lower than that required for manual shielded metal arc welding
- Extreme versatility and wide and broad application ability

Methods of Application and Position Capabilities

The most popular method of applying is the semiautomatic method, where the welder provides manual travel and guidance of a welding gun. Second is the fully automatic method, where the welding operation is automated. This process can be applied as machine welding; however, this is of minor popularity. The process cannot be applied manually.

The gas metal arc welding process is an all-position welding process. However, each of the variations has its own position capabilities, depending on electrode size and metal transfer. The CO_2 welding variation, utilizing large electrode wires, is used primarily in the flat and horizontal fillet position. The spray arc variation is normally used in the flat and horizontal position. It can be used in the vertical and overhead positions if smaller electrodes are employed. The short-circuiting and pulsed variations can be used in all positions.

Weldable Metals and Thickness Range

The gas metal arc welding process can be used to weld most metals. Carbon dioxide welding is restricted to steels. Electrodes are matched to the base metals (Figure 6-54). The process can also be used for surfacing and for buildup using special metals for bearing surfaces, corrosion-resistant surfaces, and so on.

Metal thickness from 0.005 in. (0.13 mm) upward can be welded. The short-circuiting variation and the pulsed arc variation are used for welding the thinner materials in all positions. Heavier thicknesses can be welded with large-wire CO_2 variation. Weld grooves and multiple-pass technique will allow welding of practically unlimited thickness (Figure 6-55). The extreme versatility of the process and and its variations allow welding of

	Metal Transfer Mode			
Base Metal	Short-Circuiting Arc	Spray Arc	Globular (CO_2)	Pulse Arc
Aluminums	No	Yes	No	Yes
Bronzes	No	Yes	No	Yes
Copper	No	Yes	No	Yes
Copper nickel	No	Yes	No	Yes
Cast iron	Yes	No	No	—
Magnesium	No	Yes	No	Yes
Inconel	No	Yes	No	Yes
Nickel	No	Yes	No	Yes
Monel	No	Yes	No	Yes
Low-carbon steel	Yes	Yes	Yes	—
Low-alloy steel	Yes	Yes	Yes	—
Medium-carbon steel	Yes	Yes	Yes	—
Stainless steel	Yes	Yes	No	—
Titanium	No	Yes	No	—

FIGURE 6-54 Metals weldable (GMAW).

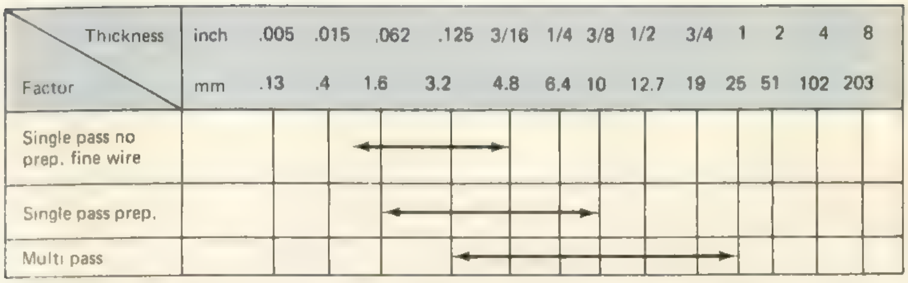


FIGURE 6-55 Base metal thickness range (GMAW).

the thinnest up to the thickest, by choosing the correct electrode wire type and size and gas for shielding.

Joint Design

The gas metal arc welding process can utilize the same joint design details that are used for the shielded metal arc welding process. These joint details are given in Chapter 19. For maximum economy and efficiency, weld joint details, specifically groove welds, should be modified. The overall diameter of the electrodes employed by gas metal arc welding are smaller than those employed for shielded metal arc welding. Because of this, the groove angles can be reduced (Figure 6-56). Reducing groove angles will still allow the electrode to be directed to the root of the weld joint so that complete penetration will occur.

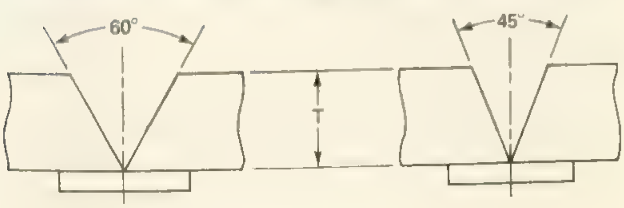
The different variations require special attention concerning weld design. The CO_2 variation provides extremely deep penetrating qualities and in designing fillet welds, the size of the fillet can be reduced at least one size when converting from shielded metal arc welding to CO_2 welding.

The variation using inert gas on nonferrous metals can use the standard joint details recommended for shielded metal arc welding, except that the groove angle should be reduced. The joint designs used for pipe welding with shielded metal arc welding or gas welding are normally used for gas metal arc welding.

Welding Circuit and Current

The welding circuit employed for gas metal arc welding (Figure 6-57) uses a wire feeder system that controls the electrode wire feed and welding arc, as well as the flow of shielding gas and cooling water. The power supply is normally the constant-voltage (CV) type. A gun or torch is used for directing the electrode and shielding gas to the arc area. A travel system is required for mechanical welding.

FIGURE 6-56 Weld joint design difference (GMAW).



The gas metal arc welding process uses direct current. Alternating current has not been successfully used. Direct current is normally used with the electrode positive DCEP (reverse polarity). Direct-current electrode negative DCEN (straight polarity) can be used with special emissive-coated electrode wires, which provide for better electron emissions. DCEN is rarely used because the emissive-coated electrodes have a short storage life.

The shorting arc variation became popular when the constant-voltage system of welding power was introduced. The constant-voltage system reduced the complexity of the wire feed control circuits and eliminated electrode burnback to the contact tip or stubbing to the work. It also provided positive arc starting.

The pulsed-current variation requires a special power source which changes from a lower to a higher current at a frequency equal to or double that of the line frequency. This is normally 50 or 60 Hz and 100 or 120 Hz.

The welding current varies from as low as 20 A at a voltage of 18 V to as high as 750 A at an arc voltage of 50 V. This broad range of current and voltage encompasses all the variations.

Equipment Required to Operate

The equipment required for a gas metal arc welding system (Figure 6-57) consists of (1) the power source, (2) the electrode wire feeder and control system, (3) the welding gun and cable assembly for semiautomatic welding or the welding torch for automatic welding, (4) the gas and water control system for the shielding gas and cooling water when used, and (5) travel mechanism and guidance for automatic welding.

Either a generator power source or a transformer-rectifier power source can be used; both are equally satisfactory. For the shorting arc variation the 200-A machine is normally used. CO_2 welding and spray arc welding require higher-current power sources up to 650

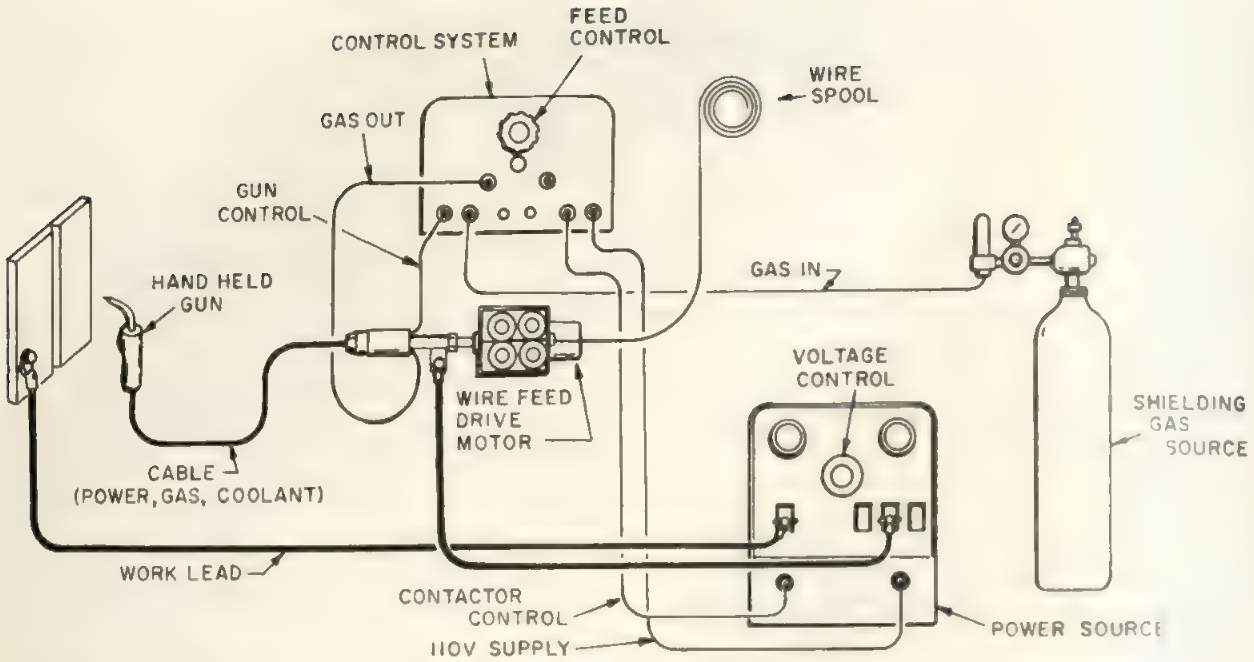


FIGURE 6-57 Block diagram (GMAW).

A; 300- and 500-A machines are the most pupular. For field use, an engine-driven generator power source is used.

The slope of the volt-ampere characteristic curve is different for the process variations. Many power sources designed for the short-circulating arc variation may have adjustable taps or other controls to vary the slope of the output curve. The smaller machines are designed for the short-circuiting arc variation. The constant-speed wire feeder is used with the CV power source since it provides a self-regulating arc. When using the pulsed-current type of power source the constant speed wire feeder is normally employed. The wire feeder must match the power source.

The welding torch or gun assembly is used to carry the electrode, the welding current, and the shielding gas to the arc. For the shorting arc variation, air-cooled welding guns are employed. When larger currents and larger-diameter electrodes are used, with CO_2 shielding gas, air-cooled guns are also used, since CO_2 is a cooling medium for the welding gun. When inert gas or the argon-oxygen mixture is used at higher currents, the gun must be water cooled. Information about manually held guns and automatic torches is given in the section on welding guns and torches.

Materials Used

Two materials are used for the gas metal arc welding process—the filler metal and the shielding gas. The electrode and the shielding gas must be carefully selected with regard to the base metal to be welded and the process variation to be employed. The filler metal or electrode wire is normally related to the strength requirements of the deposited weld metal, as well as to the composition. The following factors govern the selection of the electrode.

1. *Metal to be welded.* The type or composition and mechanical properties of the base metal are of primary importance.
2. *Thickness and Joint Design.* Thicker sections of base metal and complex joint designs usually require filler metals that provide high weld metal ductility.
3. *Surface conditions.* The surface of the base metal to be welded whether it is scaly, rusty, and so on, has an important effect on the type of electrode wire to be used.
4. *Specifications or Service Conditions.* Specifications may dictate the type of electrode to be used. If specifications are not involved, it is important to consider the service requirements that the weldment will encounter.

For mild and low-alloy steels the AWS "Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding"(15) or "Specification for Low Alloy Steel Filler Metals for Gas Shielded Arc Welding"(16) should be consulted. These specifications provide the composition of the welding electrode and the mechanical properties of the deposited weld metal. The proper electrode to match the base metals is covered in detail in the chapter on the specific base metal. The size of the electrode wire depends on the welding position and the variation of the process.

Metal Transfer	Globular	Short Circuiting	Spray	Pulsed Spray
Shielding gas	CO_2	CO_2 or CO_2 + argon (C-25)	Argon + oxygen (1–5%)	Argon + oxygen (1–5%)
Metals to be welded	Low-carbon and medium-carbon steel—low-alloy high-strength steels	Low-carbon and medium-carbon steels—low-alloy high-strength steels—some stainless steels	Low-carbon and medium-carbon steels—low-alloy high-strength steels	Aluminum, nickel, steels, nickel alloys
Metal thickness	10 gauge (0.140 in.); up to ½ in. without bevel preparation	20 gauge (0.038 in.), up to ¼ in.; economical in heavier metals for vertical and overhead welding	¼ to ½ in. with no preparation; max. thickness practically unlimited	Thin to unlimited thickness
Welding positions	Flat and horizontal	All positions (also pipe welding)	Flat and horizontal with small electrode wire all positions	All positions
Major advantages	Low-cost gas—high travel speed, deep penetration, high deposition	Thin material—will bridge gaps, min. cleanup	Smooth surface—deep penetration, high travel speed	Uses larger electrode
Limitations	Spatter removal sometimes required, high heat	Uneconomical in heavy thickness-except out of position	Position—min. thickness	Special power source
Appearance of weld	Relatively smooth, some spatter	Smooth surface—minor spatter	Smooth surface—minimum spatter	Smooth surface minimum spatter
Travel speeds	Up to 250 in./min	Max. 50 in./min	Up to 150 in./min	Up to 100 in./min
Range of electrode wire sizes (in.)	Diameter: 0.045, 1/16, 5/64, 3/32	Diameter: 0.030, 0.035, 0.045	Diameter: 0.035, 0.045, 1/16, 3/32	Diameter: 1/16, 5/64, 3/32, 1/8

FIGURE 6-58 Variations of the gas metal arc welding process.

The basis for selecting the shielding gas involves the type of electrode, the type of base metal, the welding position, the variation of the process, and the desired weld quality. The recommended shielding gases for different metals and process variations are covered in the chapter for the particular metal to be welded.

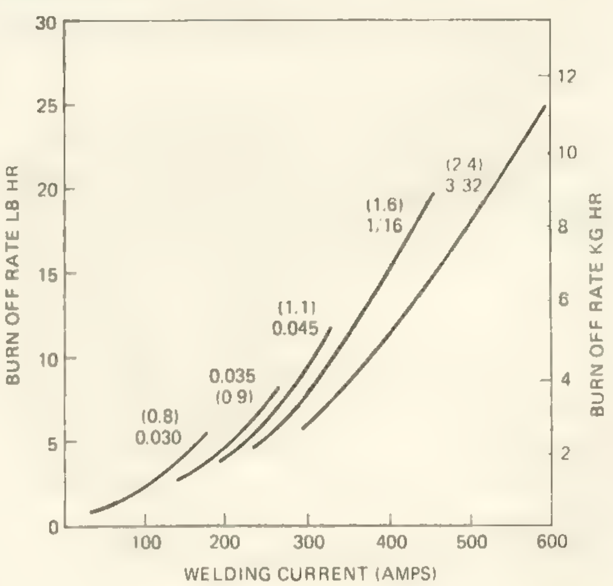
To establish a basis for selection of process variation, it is necessary to know the capabilities and normal applications for each of the process variations. Figure 6-58 shows the variations, the type of metal transfer for steel, the welding position capabilities, and the recommended welding shielding gas. This will simplify the selection of materials necessary to utilize each variation of gas metal arc welding.

Deposition Rates and Quality of Welds

Each of the variations has a considerable range of deposition rates based on the weld procedure employed. Figure 6-59 shows the relationship of deposition rates for the variations and the different electrode sizes that would be used. This chart is based on the utilization of carbon steel base metals and electrodes. For welding nonferrous metals, deposition rates vary considerably due to the density of the metals being welded.

The deposition rates of gas metal arc welding are higher for the same welding currents than are obtained with shielded metal arc welding. These higher rates occur because there is no electrode coating that must be

FIGURE 6-59 Deposition rates for variations and steel electrodes size.



melted. The current density on the small-diameter electrode wires is much higher than with covered electrodes, which contributes to the higher deposition rates for the same welding current. The tip-to-work distance affects deposition rates, and as the distance is increased, the preheating of the electrode wire contributes to higher deposition rates. Excessive stickout cannot be used without losing the ability to point the electrode wire in the joint accurately.

The quality of welds made with the gas metal arc welding process can be extremely high. The quality of the weld deposited depends on the selection of the electrode wire, the cleanliness of electrode wire, the cleanliness of the welding joint, the welding procedure, the welding position, and the skill of the welder.

Gas metal arc welding is a "no-hydrogen" or a "low-hydrogen" welding process. There is no hydrogen in the shielding gas atmosphere or in any component involved in making the weld. This is based on the use of welding-grade shielding gas and clean dry electrodes on clean, dry surfaces. Another reason for the high quality is the absence of slags and fluxes which might become entrapped in the weld.

Certain factors detract from the quality of the deposited weld metal. One is the possibility of reduced efficiency of the gas shielding envelope. Breezes in the weld area may blow the shielding gas envelope away and allow the atmosphere to come in contact with the molten puddle. The loss of shielding gas is normally noticed by the welder. This will cause a dirty-appearing weld or will create an unstable welding condition or gross porosity. Another factor is impure gas that contains water vapor, oil, or other impurities. Welding with electrode wire that is dirty, oily, or greasy will also contribute to inferior weld deposits. Anything that reduces the efficiency of the gas shield can contribute to the reduced quality of the weld. Welding on dirty surfaces—wet, oily, or otherwise—will reduce the quality of the weld metal.

Weld Schedules

The welding schedule for short-circuiting transfer or with fine-wire welding is shown in Figure 6-60. This schedule can be utilized on all types of joint details and is relatively narrow in range based on the electrode size, the welding current, and the voltage. It enables all-position welding of carbon steels on the metal thicknesses shown. In the flat position, this variation becomes less economical. For vertical and overhead welding, it is more productive than shielded metal arc welding.

The welding schedules for globular transfer CO_2 welding are shown in Figure 6-61. Here, welding currents are much higher and deposition rates and productivity are greatly increased. It is normally used in the flat and horizontal position. The basic difference between the two welding procedure schedules is the position capabilities. Note the extremely high currents that can be used on carbon steels.

For spray transfer, high currents can be employed and these data are shown by the welding procedure schedules in Figure 6-62. This is a highly productive variation for welding mild and low-alloy steels. Welding procedure schedules for nonferrous metals will be found in the chapter for each metal.

The pulsed-spray mode has two variations: fixed-frequency pulsed-current welding and variable-frequency (synergic) pulsed-current welding. Both variations utilize special power sources. Synergic is becoming the more popular. With synergic equipment the pulsed variables are programmed in the welding machine. This provides the ratio of peak to background of the pulse and the time duration of the pulse. The specific program relates to the type of metal being welded, the electrode diameter, and the shielding gas composition. The average current is adjusted by the welder; this, in turn, changes the pulsing frequency or the background current depending on the design of the machine. The manufacturer's data must be used for each welding situation. Approximate welding procedure schedules for synergic pulsed spray welding are shown in Figure 6-63.

Welding Variables

Welding procedure variables are essentially the same for all of the continuous electrode feed arc welding processes. They are items within the welding procedures that can be adjusted or changed in order to control the results. The interrelationship of the welding variables will be covered completely in Section 6-10.

Tips for Using the Process

Semiautomatic welding using the short circuiting metal transfer is easy to use. Experienced shielded metal arc welders or people with no welding experience can learn this process variation in a relatively short time. Production welding can be learned in a few days, whereas pipe welding may require 80 to 120 hours of training.[17]

It is important to use the correct welding technique when welding semiautomatically. The electrode wire should be directed to the loading edge of the puddle for optimum results. For out-of-position welding the puddle should remain small for best control.

The gun tip-to-work distance known as **stickout** must be closely controlled. If the stickout becomes too long the electrode will become overheated and will minimize penetration. Also, when the gun nozzle is too far from the arc, the shielding gas efficiency is reduced. Normal nozzle-to-work distance should be approximately 1 to 1½ times the inside diameter of the gas nozzle being used.

Another important factor is the angle the gun noz-

Material Thickness (1) Fraction	in.	mm	Electrode Dia. in.	mm	Welding Current Amps-DC	Arc Voltage Elec. Pos	Wire Feed ipm	Travel Speed ipm	Shielding Gas Flow CFH (3)
24 ga.	0.025	0.6	0.030	0.8	30-50	15-17	85 100	12-20	15-20
22 ga.	0.031	0.8	0.030	0.8	40-60	15-17	90 130	18-22	15-20
20 ga.	0.037	0.9	0.025	0.9	55-85	15-17	70 120	35-40	15-20
18 ga.	0.050	1.3	0.035	0.9	70-100	16-19	100 160	35-40	15-20
1/16	0.063	1.6	0.035	0.9	80-110	17-20	120 180	30-35	20-25
5/64	0.078	2.0	0.035	0.9	100-130	18-20	160 220	25-30	20-25
1/8	0.125	3.2	0.035	0.9	120-160	19-22	210 290	20-25	20-25
1/8	0.125	3.2	0.045	1.1	180-200	20-24	210 240	27-32	20-25
3/16	0.187	4.7	0.035	0.9	140-160	19-22	210 290	14-19	20-25
3/16	0.187	4.7	0.045	1.1	180-205	20-24	210 245	18-22	20-25
1/4	0.250	6.4	0.035	0.9	140-160	19-22	240 290	11-15	20-25
1/4	0.250	6.4	0.045	1.1	180-225	20-24	210 290	12-18	20-25

Note: Singlepass flat and horizontal fillet position. Reduce current 10 to 15% for vertical and overhead welding.

(1) For fillet and groove welds. For fillet welds size equals metal thickness. For square groove welds the root opening should equal 1/2 the metal thickness.

(3) Shielding gas is CO_2 or mixture of 75% Argon + 25% CO_2.

FIGURE 6-60 Short-circuiting transfer schedules.

FIGURE 6-61 Globular transfer (CO_2) schedules.

Material Thickness Ga.	in.	mm	Type of Weld (a)	Electrode Dia. in.	mm	Welding Current Amps-DC	Arc Voltage Elec. Pos.	Wire Feed ipm	Travel Speed ipm	CO_2 Gas Flow CFH
18	0.050	1.3	Fillet	0.045	1.1	280	26	350	190	20-25
			square groove	0.045	1.1	270	25	340	180	20-25
16	0.063	1.6	Fillet	0.045	1.1	325	26	360	150	30-35
			square groove	0.045	1.1	300	28	350	140	30-35
14	0.078	2.0	Fillet	0.045	1.1	325	27	360	130	30-35
			square groove	0.045	1.1	325	29	360	110	30-35
			square groove	0.045	1.1	330	29	350	105	30-35
11	0.125	3.2	Fillet	1/16	1.6	380	28	210	85	30-35
			square groove	0.045	1.1	350	29	380	100	30-35
3/16	0.188	4.8	Fillet	1/16	1.6	425	31	260	75	30-35
			square groove	1/16	1.6	425	30	320	75	30-35
			square groove	1/16	1.6	375	31	260	70	30-35
1/4	0.250	6.4	Fillet	5/64	2.0	500	32	185	40	30-35
			square groove	1/16	1.6	475	32	340	55	30-35
3/8	0.375	9.5	Fillet	3/32	2.4	550	34	200	25	30-35
			square groove	3/32	2.4	575	34	160	40	30-35
1/2	0.500	12.7	Fillet	3/32	2.4	625	36	160	23	30-35
			square groove	3/32	2.4	625	35	200	33	30-35

(1) For mild carbon and low alloy steels on square groove welds backing is required.

Material Thickness in. (1)	mm	Type of Weld	Number of Passes	Electrode Dia. in.	mm	Welding Current Amps-DC	Arc Voltage Elec. Pos.	Wire Feed ipm	Travel Speed ipm	Shielding Gas (2) Flow CFH
		Fillet or								
1/8	3.2	square groove	1	1/16	1.6	300	24	165	35	40-50
		Fillet or								
3/16	4.8	square groove	1	1/16	1.6	350	25	230	32	40-50
		Vee				325	24	210		
1/4	6.4	groove	2	1/16	1.6	375	25	260	30	40-50
		Vee				400	26	100		
1/4	6.4	groove	2	3/32	2.4	450	29	120	35	40-50
1/4	6.4	Fillet	1	1/16	1.6	350	25	230	32	40-50
1/4	6.4	Fillet	1	3/32	2.4	400	26	100	32	40-50
		Vee				325	24	210		
3/8	9.5	groove	2	1/16	1.6	375	25	260	24	40-50
		Vee				400	26	100		
3/8	9.5	groove	2	3/32	2.4	450	29	120	28	40-50
3/8	9.5	Fillet	2	1/16	1.6	350	25	230	20	40-50
3/8	9.5	Fillet	1	3/32	2.4	425	27	110	20	40-50
		Vee				325	24	210		
		groove				375	26	260		
1/2	12.7		3	1/16	1.6	375	26	250	24	40-50
		Vee				400	26	100		
		groove				450	29	120		
1/2	12.7		3	3/32	2.4	425	27	110	30	40-50
1/2	12.7	Fillet	3	1/16	1.6	350	25	230	24	40-50
1/2	12.7	Fillet	3	3/32	2.4	425	27	105	26	40-50
								110		
		Double				325	24	210		
		Vee				375	26	260		
3/4	19.1	Groove	4	1/16	1.6	350	25	230	24	40-50
		Double				400	26	100		
		Vee				450	29	120		
3/4	19.1	Double	4	3/32	2.4	425	27	110	24	40-50
3/4	19.1	Fillet	5	1/16	1.6	350	25	230	24	40-50
3/4	19.1	Fillet	4	3/32	2.4	425	27	110	26	40-50
1	24.1	Fillet	7	1/16	1.6	350	25	230	24	40-50
1	24.1	Fillet	6	3/32	2.4	425	27	110	26	40-50

Use only in flat and horizontal fillet position.

(1) For fillet welds, material thickness indicates fillet weld size.

(2) Shielding gas is argon plus 1 to 5% oxygen.

FIGURE 6-62 Spray arc transfer schedules.

zle makes with the work. Two angles are involved. One is known as the *travel angle*, the other is the *work angle*. The work angle is normally half the included angle between the plates forming the joint. When making fillet welds the gun should be at a 45° angle but directed slightly toward the horizontal plate by one electrode wire diameter from the bisecting angle.

The travel angle can be a *drag angle* or a *push angle*. The push angle pointing forward is used when pure inert gases are employed. The drag angle pointing backward is used when CO_2 is used—with short circuiting or the globular transfer.

The welding equipment must be in good operating condition. The drive rolls and contact tip must be proper for the electrode size being used. The conduit tube in the gun cable assembly must be kept clean and any centering guides, lineup rolls, and so on, must be properly aligned. The nozzle of the gun must be kept clean and all portions of the gas supply system must be tight and operating properly. Finally, the work cable must be tightly connected to the work for trouble-free operation.

The welding parameters must be set in accordance with welding procedure schedules. The correct gas flow rates must be employed for optimum results. The welding polarity must be correct. For almost all gas metal arc welding, direct current electrode positive is employed. The proper inductance or tap should be used and all other adjustments should be in order.

Material Thickness			Electrode Diameter		Average Current (A)	Peak Current (A)	Background Current (A)	Arc Voltage (Electrode) positive)
Ga	in.	mm	in.	mm				
22	0.031	0.8	0.035	0.9	50	150	20	16
20	0.037	0.9	0.035	0.9	60	160	20	17
18	0.050	1.3	0.035	0.9	70	180	20	18
16	0.063	1.6	0.045	1.2	80	200	25	19
14	0.078	2.0	0.045	1.2	90	250	35	21
11	0.125	3.2	0.045	1.2	120	250	150	22
3/16	0.188	4.8	0.045	1.2	150	250	200	23
1/4	0.250	6.4	0.052	1.3	120	275	90	24
3/8	0.375	9.5	0.052	1.3	200	350	150	26

Note: For square groove or fillet, use root opening ½ material thickness. Fillet equal to thickness. For mild carbon and low-alloy steels, shielding gas 95% argon + 5% oxygen.

Material Thickness			Wire Feed Speed		Travel Speed		Shielding Gas Flow	
Ga	in.	mm	in./min	mm/min	in./min	mm/min	ft^3/min	liters/min
22	0.031	0.8	75	1900	30	760	20	9
20	0.037	0.9	90	2300	30	760	20	9
18	0.050	1.3	115	2900	30	760	20	9
16	0.063	1.6	80	2000	20	500	25	12
14	0.078	2.0	120	3000	20	500	25	12
11	0.125	3.2	200	5000	15	375	25	12
[illegible]	0.188	4.8	240	6000	10	250	25	12
[illegible]	0.250	6.4	215	5500	9	225	25	12
[illegible]	0.375	9.5	300	7500	8	200	25	12

FIGURE 6-63 Pulsed spray transfer schedules, variable-frequency (synergic) variation.

Safety Considerations

Safety factors and potential hazards involved with the gas metal arc welding process are covered in detail in Chapter 3. In general, gas metal arc welding is a less hazardous process than manual shielded metal arc welding.

Limitations of the Process

There are very few limitations to the overall process if each of the variations is considered. Some of the early limitations are mentioned but most of these have been overcome.

One problem has been the inability to reach inaccessible welding areas with the available guns. Gas metal arc welding guns are not as flexible as the covered electrode used for shielded metal arc welding. However, extensions can be placed on welding guns to reach relatively inaccessible areas. A variety of guns is shown in Figure 6-64.

There has been some concern about the inability to push small-diameter, soft electrode wires through long cable assemblies. There are several solutions to this. One is the spool gun feeder with the wire supply mounted on a welding gun and pushed only a very short distance. This type of wire feeder has been popular for welding aluminum. Another solution is the use of a linear wire feed motor in the gun handle. The linear booster motor is also used at the wire supply. It is extremely popular for aluminum, but is also used for feeding other electrode wire types.

Often there is the objection of higher-priced equipment that requires additional maintenance. When comparing gas metal arc welding to manual shielded metal arc welding, it is obvious that more equipment is involved. The productivity of GMAW is sufficiently greater to make the extra cost and extra maintenance a minor factor from an overall cost viewpoint.

Another objection to the process has been the problem of wind and drafts affecting the efficiency of the gas shielding envelope around the arc area. This can be a problem when working outdoors or in drafty locations. It can be overcome by establishing wind breaks or shielding the welding area from direct exposure to fans or open doors or the wind. With a little experience welders are able to use their body to shield the arc area from drafts and breezes.

Variations of the Process

The variations of the process are mentioned throughout this section. They have a great effect on the selection of

FIGURE 6-64 Gun nozzle extensions.

the variation for particular applications. There are some applications which can be considered process variations, such as narrow gap welding and arc spot welding. Both are explained in Chapter 26.

Industrial Use and Typical Applications

An early use for gas metal arc welding was for welding nonferrous metals primarily of the heavier thicknesses. A typical application is the welding of aluminum bus bars in the electrical industry (Figure 6-65).

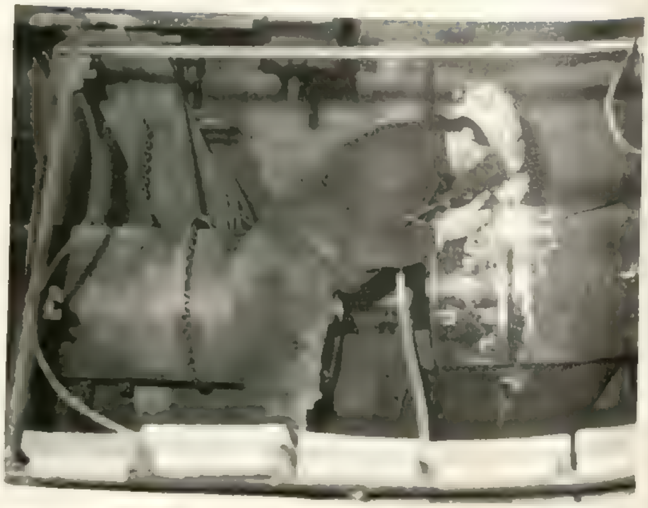
The most aggressive user of the process has been the sheet metal industry. Many submerged arc welding applications have been changed to gas metal arc welding since it is better for automatic fixturing and avoids the problem of abrasive flux in fixtures. A typical application is the semiautomatic welding of a sheet metal assembly (Figure 6-66).

Pipe welding also utilizes the gas metal arc welding process. A typical application is shown in Figure 6-67. Here all-position welding is performed at a speed higher than previously obtained with shielded metal arc welding. There are many, many applications of the process.

FIGURE 6-65 Welding aluminum bus bar

FIGURE 6-66 Welding sheet metal assembly.

FIGURE 6-67 Welding pipe.



6-5 FLUX-CORED ARC WELDING

The flux-cored arc welding (FCAW) process is an arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding gas from flux contained within the tubular electrode with or without additional shielding from an externally supplied gas, and without the application of pressure. The welder's view of this arc welding process is shown in Figure 6-68.

There are two variations, one using externally supplied shielding gas and a second which relies entirely on shielding gas generated from the disintegration of flux within the electrode. Flux-cored arc welding is almost identical to gas metal arc welding except for the electrode. In some countries, flux-cored arc welding is considered a variation of GMAW.

FIGURE 6-68 Welder's view of flux-cored arc using CO_2 shielding gas.

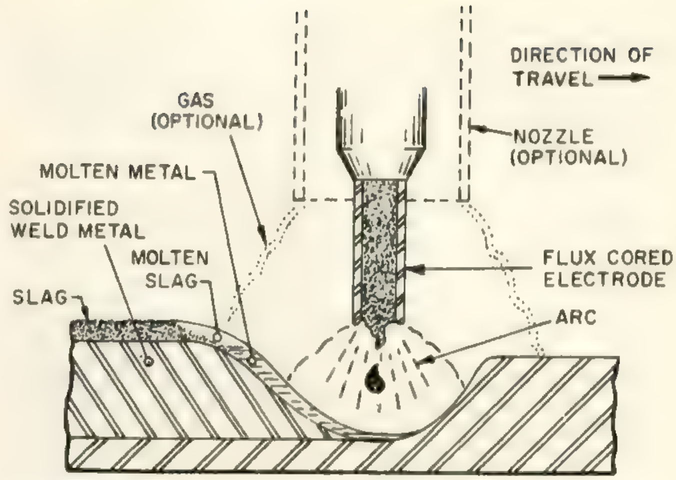


FIGURE 6-69 Process diagram (FCAW).

Principle of Operation

The flux-cored arc welding process (Figure 6-69) utilizes the heat of an arc between a continuously fed consumable flux-cored electrode and the work. The heat of the arc melts the surface of the base metal and the end of the electrode. The metal melted off the electrode is transferred through the arc to the work piece where it becomes the deposited weld metal. Shielding is obtained from the disintegration of ingredients contained within the flux-cored electrode. Additional shielding is obtained from an envelope of gas supplied through a nozzle to the arc area. Ingredients within the electrode produce gas for shielding and also provide deoxidizers, ionizers, purifying agents, and in some cases alloying elements. These ingredients form a glasslike slag, which is lighter in weight than the deposited weld metal, and floats on the surface of the weld as a protective cover. The electrode is fed into the arc automatically, from a coil. The arc is maintained automatically and travel can be manual or by machine.

Advantages and Major Uses

The flux-cored arc welding process introduced in early 1950 is an outgrowth of the gas metal arc welding process. Flux-cored arc welding has many advantages over the manual shielded metal arc welding process. It also provides certain advantages over submerged arc welding and the gas metal arc welding processes. Simply stated, the flux-cored arc welding process provides high-quality weld metal at lower cost with less effort on the part of the welder than shielded metal arc welding. It is more forgiving than gas metal arc welding and is more flexible and adaptable than submerged arc welding. These advantages can be listed as follows:

- ☐ High-quality weld metal deposit
- ☐ Excellent weld appearance: smooth, uniform welds
- ☐ Excellent contour of horizontal fillet welds
- ☐ Welds a variety of steels over a wide thickness range
- ☐ High operating factor: easily mechanized
- ☐ High deposition rate: high-current density
- ☐ Relatively high electrode metal utilization
- ☐ Relatively high travel speeds
- ☐ Economical engineering joint designs
- ☐ Visible arc: easy to use
- ☐ Less precleaning required than for gas metal arc welding
- ☐ Reduced distortion over shielded metal arc welding

This process is becoming increasingly popular. It is widely used on medium thickness steel fabricating work, where the fine wire gas metal arc welding process would not apply and where the fitup is such that submerged arc welding would be unsuitable.[18]

Methods of Application and Position Capabilities

The most popular method of applying flux-cored arc welding is by the semiautomatic method. Second is the fully automatic method. The process can also be applied by machine methods, but it cannot be applied manually. The flux-cored arc welding process is an all-position welding process depending on electrode size.

Weldable Metals and Thickness Range

The flux-cored arc welding process is used to weld low- to medium-carbon steels, low-alloy high-strength steels, quenched and tempered steels, certain stainless steels, and cast iron. The process is also used for surfacing and for buildup. The metals welded by the process are shown in Figure 6-70.

The metal thickness range for the two variations—self-shielding and using CO_2 external gas shielding—is different. With a CO_2 atmosphere weld penetration is considerably deeper and metal thicknesses from 1/16 in. (1.6 mm) to ½ in. (13 mm) can be welded with no edge preparation when CO_2 gas is used. When CO_2 gas is not used the maximum is only one half or ¼ in. (6 mm). With edge preparation, welds can be made with a single pass on material from ¼ in. (6 mm) through ¾ in. (19 mm), with either variation. With a multipass technique and joint preparation, the maximum thickness is practically unlimited (Figure 6-71). Horizontal fillets can be made up to ⅜ in. (9.5 mm) in a single pass, and in the flat position fillet welds can be made to ¾ in. (19 mm).

FIGURE 6-70 Metals weldable (FCAW).

Base Metal	Weldability
Cast iron	Using special electrode
Low carbon steel	Weldable
Low alloy steel	Weldable
High and medium carbon	Weldable
Alloys steel	Weldable
Stainless steel—selected	Limited types

Joint Design

The flux-cored arc welding process can utilize the same joint design details used by the shielded metal arc welding process. These joint details are given in Chapter 19. For maximum utilization and efficiency, different joint details are suggested.

For groove welds, the square groove design can be used up to ⅝ in. (16 mm) thickness. Beyond this thickness, bevels are required; however, the included angle of bevel groove welds can be reduced 35 to 50% over that normally used for shielded metal arc welding. This is because the smaller size electrode wire can get deeper into the joint. Open roots can be used; however, a root face is normally required to avoid burning through. In many structural applications the weld is made with a tight root opening, and the back side is gouged and rewelded. When welding fillet welds using the CO_2 shielded version, the fillet size can be smaller yet will have the same strength as shielded metal arc welds (Figure 6-72). The self-shielding type electrode wire does not have the deep penetrating qualities of the CO_2 deposit; therefore, the fillet size cannot be reduced when using this variation.

Welding Circuit and Current

The welding circuit employed for flux-cored arc welding is identical to that used by the gas metal arc welding process (Figure 6-73). In the case of self-shielding electrode wires, the gas system is eliminated.

The flux-cored arc welding process normally uses direct current with the electrode positive (DCEP). Some electrodes for the self-shielding variation operate with the electrode negative (DCEN). Direct current with constant-voltage power is normally employed.

Ac flux-cored arc welding is used in some situations with specially formulated flux-cored electrodes. When ac electrodes are used, a drooping characteristic (CC) type of power source and voltage-sensing feeders are employed. The welding current for flux-cored arc welding can vary from as low as 50 A to as high as 750 A.

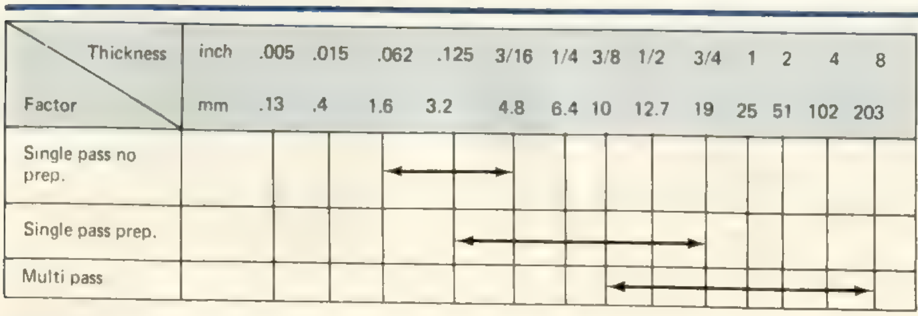


FIGURE 6-71 Base metal thickness range (FCAW).

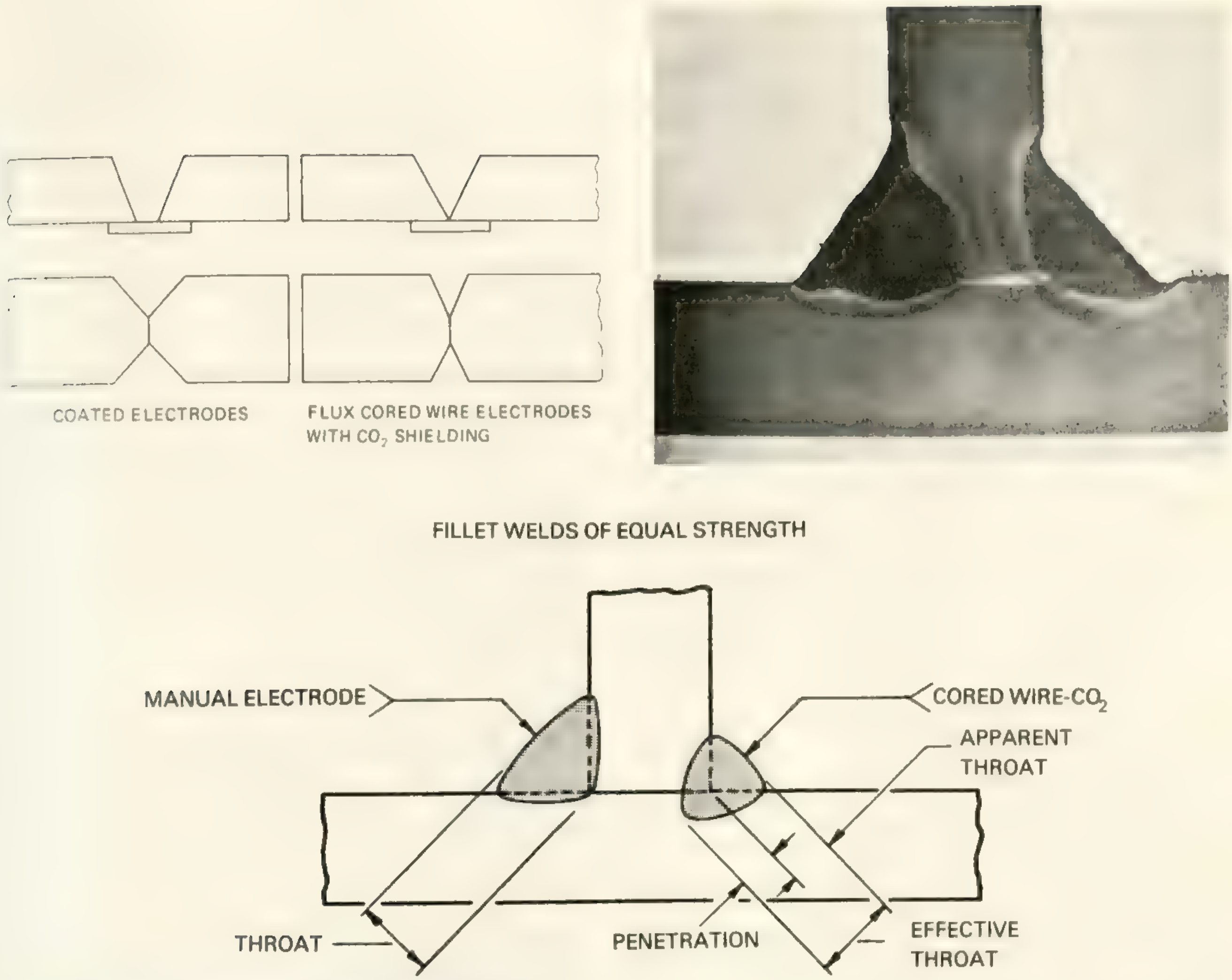
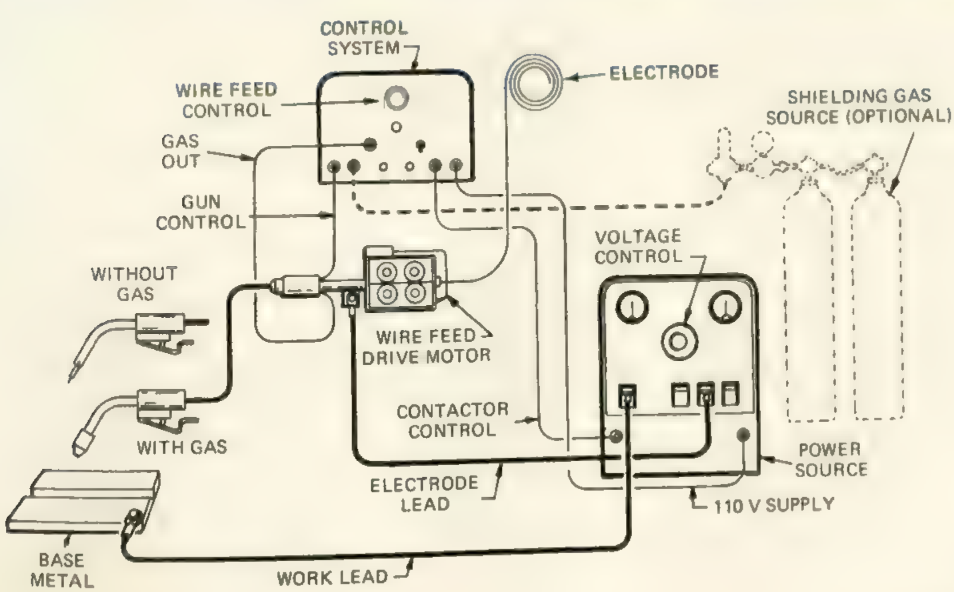


FIGURE 6-72 Welding joint design details (FCAW).

FIGURE 6-73 Circuit diagram (FCAW).



Equipment Required to Operate

The equipment required for flux-cored arc welding is shown in Figure 6-73. These components, when using the externally gas shielded version, are identical to the gas metal arc welding process. The only difference is that higher current power sources and larger welding guns or torches are used.

When the gasless version is used, the entire shielding gas supply system is eliminated. This eliminates the gas cylinders, the regulator and flow meter, the hoses, the solenoid valve, and the nozzle on the welding gun. Since the nozzle is removed from the welding guns, the guns can be designed with different tip configurations. The end of the welding gun is smaller and visibility is improved. However, in view of the amount of smoke produced by flux-cored welding, it is becoming increasingly necessary to include smoke suction nozzles surrounding the gun nozzle to reduce smoke and fumes. Guns for self-shielding electrodes normally use special wire guides that include *electrical stickout*. This means that the current is introduced to the electrode before the end of the tip. This preheats the electrode wire and makes it more productive. More information on guns and torches is given in the section on welding guns and torches.

Materials Used

Two materials are required, the electrode and the shielding gas. The difference between gas metal arc welding and flux-cored welding is the electrode. There are several reasons why the cored electrode wires were developed to supplement solid wires of the same or similar analysis. Solid electrode wires are drawn from billets of the proper specific analysis, which may not be readily available and are large and expensive. In the case of cored wires, the special alloying elements are introduced in the core material to provide the proper deposit analysis. Second, the cored wire production method provides a latitude of composition which is not limited to the analysis of steel billets available. Third, the cored electrode wires are easier for the welder to use than solid wires of the same deposit analysis. This is especially true for alloy-type welding on pipe in the fixed position.

A series of flux-cored electrode wires have been developed and specifications established. The information concerning these electrodes is based on the AWS specifications for flux-cored electrodes.[19,20] These specifications and a discussion of the manufacture of electrodes are given in Chapter 13. Figure 6-74 provides information about their classification and usage.

The self-shielding flux-cored electrode wires include additional gas-forming elements in the core. These are necessary to prohibit the oxygen and nitrogen of the air from contacting the metal transferring across the arc and the molten weld pool. In addition, self-shielding electrodes include extra deoxidizing and denitrating elements to compensate for oxygen and nitrogen which may contact the molten metal. Self-shielding electrodes are usually more voltage sensitive and require electrical stickout for smooth operation. The properties of the weld metal deposited by the self-shielding wires are sometimes less than those produced by the externally shielded electrode wires, because of the extra amount of deoxidizers included. It is possible for these elements to build up in multipass welds, lower the ductility, and reduce the impact values of the deposit. Many codes prohibit the use of self-shielding wires on steels with the yield strength exceeding 42,000 psi (25.5 kg/mm²). Other codes prohibit the self-shielding wires from being used on dynamically loaded structures.

The other material used with gas shielded flux-cored

AWS Classification	Composition and Specification	Shielding Gas	Current and Polarity	Welding Technique
EXXT-1	Carbon steel and low-alloy steel A5.20 and A5.29	CO_2	DCEP	Multiple
EXXT-2		CO_2	DCEP	Single
EXXT-3		None	DCEP	Single
EXXT-4		None	DCEP	Multiple
EXXT-5		CO_2	DCEP	Multiple
EXXT-6		None	DCEP	Multiple
EXXT-7		None	DCEN	Multiple
EXXT-8		None	DCEN	Multiple
EXXT-10		None	DCEN	Single
EXXT-11		None	DCEN	Multiple
EXXT-G		Note	Note	Multiple
EXXT-GS		Note	Note	Single
EXXXT-1	Chrominum–Nickel steel A5.22	CO_2	DCEP	Not specified
EXXXT-2		Argon + 2% O	DCEP	Not specified
EXXXT-3		None	DCEP	Not specified
EXXXT-G		Not specified	Not specified	Not specified

Note: As agreed upon between supplier and user.

FIGURE 6-74 Summary of specification for flux-cored electrodes.

arc welding is the shielding gas. Carbon dioxide is used most often. However, the CO_2–argon mixture (75% argon plus 25% CO_2) and the argon-oxygen mixtures are sometimes used. These gas mixtures are used for out-of-position welding, for welding piping or when an extra smooth weld is required. It is important to know if an electrode can be used with a gas mixture since the majority of the electrodes are designed for use with CO_2 shielding. Caution should be exercised to determine if this will be detrimental to the weldment. Certain of the deoxidizers included in the electrode wire, such as silicon, manganese, and possible aluminum, will carry across the arc rather than be oxidized in the arc. These elements may build up in multiple-pass welds to a level that could be unacceptable.

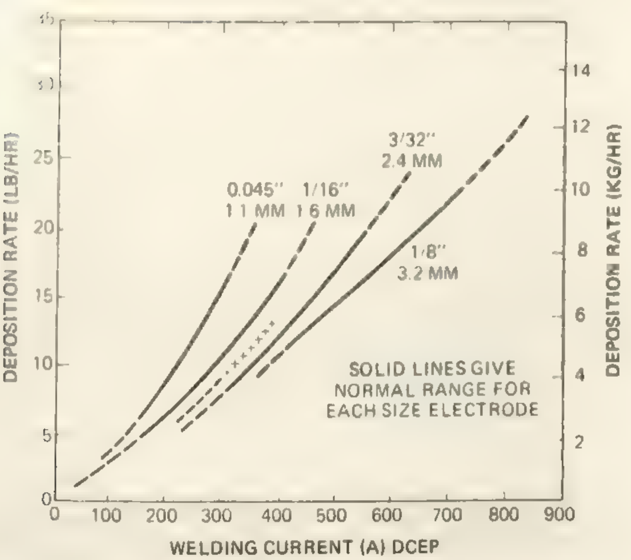
Deposition Rates and Quality of Welds

The deposition rates for flux-cored electrodes are shown in Figure 6-75. These curves show deposition rates when welding with mild and low-alloy steels using direct-current electrode positive (DCEP). Deposition rates of the smaller size flux-cored wires exceed that of the covered electrodes. The metal utilization of the flux-cored electrode is higher. Flux-cored electrodes have a much broader current range than covered electrodes, which increases the flexibility of the process.

The quality of the deposited weld metal produced by the flux-cored welding process depends primarily on the flux-cored electrode that is used. It can be expected that the deposited weld metal will match or exceed the properties shown for the electrode used. This assures the proper matching of base metal, flux-cored electrode type and shielding gas. Quality depends on the efficiency of the gas shielding envelope, on the joint detail, on the cleanliness of the joint, and on the skill of the welder.

The quality level of weld metal deposited by the self-shielding electrode wires is usually lower than that produced by electrodes that utilize external gas shielding. This is recognized by reviewing the properties of the deposited metal of both types of electrodes. As time goes by, the self-shielding electrodes will be improved to provide higher levels of quality.

FIGURE 6-75 Deposition rates of steel flux-cored electrodes.



Weld Schedules

The welding procedure schedules for flux-cored arc welding are given in two ways. The first is shown in Figure 6-76, which provides information for using electrode-positive electrodes and electrode-negative electrodes. The welding parameters are given for each size of electrode for welding in different positions. In this or any welding procedure schedule, the ranges can be expanded. Higher currents can be used when automatic travel is used. The voltage range can also be expanded and will increase when a longer tip-to-work or stickout distance is used. Normally, for the 0.45-in. (1.1-mm) size, the stickout is $\frac{1}{2}$ to $\frac{5}{8}$ in. For the $\frac{1}{16}$-in. (1.6-mm) size, the stickout is increased to $\frac{3}{4}$ in., and for the $\frac{5}{64}$-in. (2.0-mm) size and above, the stickout is increased to $\frac{3}{4}$ to 1 in. CO_2 shielding gas is used with the electrode-positive electrode in the range 35 ft^3 per hour (16.5 liter per minute). Wire feed speed is given, which provides a deposition rate.

The second set of tables for welding procedure schedules is shown in Figure 6-77. In this series specific weld details are shown and weld schedules are given for each detail. This is based on generalized conditions using manual travel on carbon steel, and can be altered for specific situations. These tables are starting points and should be verified by qualification tests or production runs. The weld cross-sectional area for flux-cored welding can be reduced over that utilized for coated electrodes and for this reason joint details shown on these charts can be modified to reduce the included angle.

When utilizing the self-shielding type wires that operate with direct current electrode negative (DCEN) current levels are reduced approximately 20%. Electrical stickout is required for most self-shielding electrodes. The amount varies by electrode type.

Welding Variables

The welding variables involved with flux-cored arc welding are essentially the same as those associated with gas metal arc welding. Flux-cored arc welding does have an extremely wide range of welding current and voltage. These are quite different for the electrodes that operate electrode positive and those that operate electrode negative. This information is summarized in Figure 6-78, which shows the operating range for both types.

Welding Data: For CO_2 Gas-Shielded Electrode with Reverse Polarity[a]

Diameter		Weld				Wire Feed Speed		Deposition Rate		Stickout
in.	mm	Position	Amperage	Current	Voltage	in./min	mm/min	lb/hr	kg/hr	± ¼ in.
0.045	1.1	Flat–horiz.	150	DCEP	25	225	75,715	3.5	1.58	¾
0.045	1.1	Flat–horiz.	180	DCEP	27	280	7,112	5.3	2.40	¾
0.045	1.1	Flat	250	DCEP	29	450	11,430	8.0	3.63	¾
1/16	1.6	Flat–horiz.	200	DCEP	25	138	3,505	4.7	2.13	¾
1/16	1.6	Flat–horiz.	250	DCEP	26	177	4,495	6.0	2.72	¾
1/16	1.6	Flat–horiz.	300	DCEP	27	230	5,842	8.4	3.81	¾
1/16	1.6	Flat	350	DCEP	28	280	7,112	10.9	4.94	¾
1/16	1.6	Flat	375	DCEP	29	311	7,899	11.6	5.28	¾
5/64	2.0	Flat–horiz.	250	DCEP	26	119	3,040	6.6	2.99	1
5/64	2.0	Flat–horiz.	300	DCEP	29	145	3,683	8.4	3.51	1
5/64	2.0	Flat–horiz.	350	DCEP	31	181	4,597	10.2	4.53	1
5/64	2.0	Flat	400	DCEP	33	226	5,740	12.1	5.49	1
3/32	2.4	Flat–horiz.	350	DCEP	26	120	3,048	9.2	4.17	1
3/32	2.4	Flat–horiz.	400	DCEP	29	142	3,606	11.5	5.22	1
3/32	2.4	Flat	450	DCEP	32	174	4,419	13.7	6.21	1
3/32	2.4	Flat	500	DCEP	34	201	5,105	15.2	6.89	1
3/32	2.4	Flat	550	DCEP	36	234	5,943	18.1	8.21	1
7/64	2.8	Flat	500	DCEP	30	125	3,175	13.4	6.08	1
7/64	2.8	Flat	550	DCEP	32	145	3,683	15.5	7.03	1
7/64	2.8	Flat	600	DCEP	34	176	4,470	18.5	8.39	1
7/64	2.8	Flat	650	DECP	36	196	4,978	20.6	9.34	1
7/64	2.8	Flat	700	DCEP	36	221	5.613	23.6	10.70	1
⅛	3.2	Flat	600	DCEP	32	120	3,048	17.8	8.07	1
⅛	3.2	Flat	650	DCEP	34	130	3,302	19.7	8.93	1
⅛	3.2	Flat	700	DCEP	36	143	3,632	21.4	9.70	1
⅛	3.2	Flat	750	DCEP	38	155	3,937	22.0	9.97	1
⅛	3.2	Flat	800	DCEP	38	166	4,216	24.6	10.88	1

[a]Use CO_2 shielding gas at 35 to 40 ft³/hr. (16 to 19 liters/min.)

Welding Data: For Self-Shielding Electrode on Straight Polarity

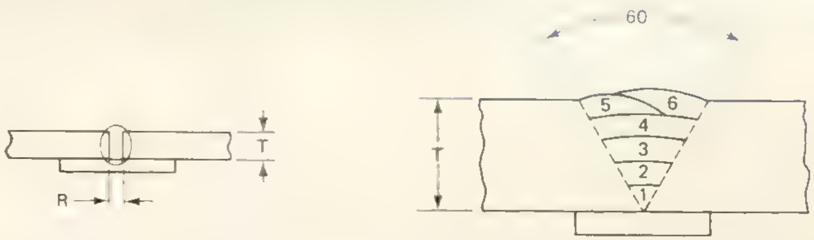
Diameter		Weld				Wire Feed Speed		Deposition Rate		Stickout
in.	mm	Position	Amperage	Current	Voltage	in./min	mm/min	lb/hr	kg/hr	± ¼ in.
0.045	1.1	Flat	130	DCEN	15	105	2667	1.80	0.82	½
0.045	1.1	Flat fillet	160	DCEN	17	170	4318	2.76	1.25	½
0.045	1.1	Horiz. fillet	160	DCEN	16.5	170	4318	2.76	1.25	½
0.045	1.1	Vert.-up fillet	130	DCEN	16	125	3175	1.80	0.82	½
0.045	1.1	Ovhd. fillet	130	DCEN	16	125	3175	1.80	0.82	½
1/16	1.6	Flat	150	DCEN	18	70	1778	2.40	1.09	¾
1/16	1.6	Horiz. fillet	200	DCEN	19	99	2514	3.54	1.61	¾
1/16	1.6	Flat	250	DCEN	20	144	3675	5.88	2.67	¾
.068	1.7	Flat	175	DCEN	18.5	49	1244	1.92	0.87	¾
.068	1.7	Horiz. fillet	200	DCEN	20	94	2387	3.54	1.61	¾
.068	1.7	Flat	200	DCEN	20	94	2387	3.54	1.61	¾
.068	1.7	Flat	225	DCEN	21	111	2819	5.16	2.34	¾
.068	1.7	Flat	275	DCEN	22	159	4038	7.38	3.35	¾
5/64	2.0	Horiz. fillet	200	DCEN	19	67	1701	3.30	1.50	¾
5/64	2.0	Horiz. fillet	250	DCEN	21	90	2286	5.52	2.50	¾
5/64	2.0	Flat	300	DCEN	22.5	124	3170	7.50	3.40	¾
3/32	2.4	Flat	250	DCEN	18.5	57	1447	4.98	2.26	¾
3/32	2.4	Flat	300	DCEN	20	75	1905	6.48	2.94	¾
3/32	2.4	Horiz. fillet	300	DCEN	21.5	75	1905	6.48	2.94	¾
3/32	2.4	Flat	300	DCEN	21.5	75	1905	6.48	2.94	¾

[a]No external shielding gas used.

FIGURE 6-76 Welding procedure schedule (FCAW).

FIGURE 6-77 Welding procedure schedule: joint details.

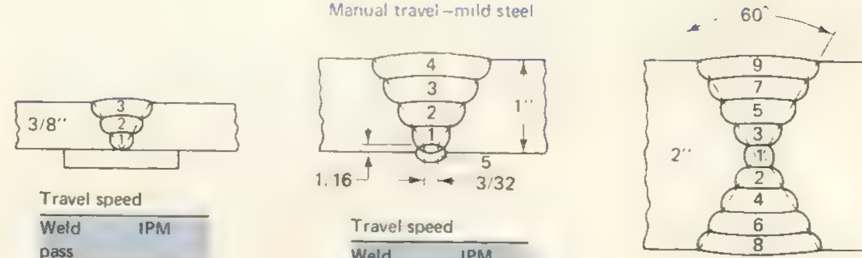
Mild steel with backup



Material Thickness T in.	mm	Type of Joint	Number of Passes	Root Opening R in.	mm	Electrode Diameter in.	mm	Welding Power Volts EP	Amps DC	Travel Speed per pass, ipm
1/8	3.2	square	1	1/32	0.8	3/32	2.4	24-26	325	56
1/4	6.4	60 vee	1	0	0	3/32	2.4	25-27	375	41
1/2	1.27	60 vee	1	0	0	1/8	3.2	27-30	550	14
3/4	19.0	60 vee	3	0	0	1/8	3.2	27-30	550	18
1	25.4	60 vee	6	0	0	1/8	3.2	27-30	550	11

(a)

Manual travel—mild steel



Travel speed

Weld pass	IPM
1	13 down
	7.7 up
	5 up

Travel speed

Weld pass	IPM
1	13 down
2	1.4 up
3	2.3 up
4	1.6 up
5	11 down

Travel speed

Weld pass	IPM
1	11 down
2	3 up
3	3.5 up
4	2.1 up
5	2.7 up
6	2 up
7	1.8 up
8	1.4 up
9	1.3 up

Material Thickness T in.	mm	Type of Joint	Number of Passes	Root Opening in.	mm	Electrode Diameter in.	mm	Volts EP	Amps DC
3/8	9.5	60 single vee	3	0	0	.045	1.1	22	180
1	25.4	60 single vee	5	3/32	2.4	.045	1.1	22	180
2	50.8	60° single vee	9	1/16	1.6	.045	1.1	22	180

(b)

Weld Size (S) in.	mm	Material Thickness T in.	mm	Number of Passes	Electrode Diameter in.	mm	Welding Power Volts EP	Amps DC	Travel Speed IMP (per pass)
1/8	3.2	1/8	3.2	1	3/32	2.4	24-26	300-350	44-60
1/4	6.4	1/4	6.4	1	3/32	2.4	24-26	350-400	22-24
1/4	6.4	1/4	6.4	1	1/8	3.2	25-27	450-500	26-30
3/8	9.5	3/8	9.5	1	3/32	2.4	26-30	375-500	13-17
3/8	9.5	3/8	9.5	1	1/8	3.2	28-31	500-575	16-20
5/8	15.9	5/8	15.9	3	3/32	2.4	26-31	450-475	12-14
5/8	15.9	5/8	15.9	3	1/8	3.2	27-30	450-500	12-14

(c)

Welding Range for E70T-1 with CO_2 Shielding: DCEP

Diameter		Minimum				Maximum			
				Wire Feed Speed				Wire Feed Speed	
in.	mm	Amperes	Volts	in./min	mm/min	Amperes	Volts	in./min	mm/min
0.045	1.2	120	21	168	4267	300	30	625	15,875
1/16	1.6	150	24	100	2540	425	31	400	10,160
5/64	2.0	200	26	95	2413	450	33	270	6,858
3/32	2.4	300	26	95	2413	600	36	255	6,477
7/64	2.8	450	30	110	2794	750	38	237	6,019
1/8	3.2	550	32	98	2489	850	39	175	4,445

Welding Range for E71T-11 Self-Shielding: DCEN

Diameter		Minimum				Maximum			
				Wire Feed Speed				Wire Feed Speed	
in.	mm	Amperes	Volts	in./min	mm/min	Amperes	Volts	in./min	mm/min
0.045	1.1	95	13	65	1651	180	18.5	200	5080
1/16	1.6	100	15	47	1193	300	22	189	4800
0.068	1.7	125	17	49	1245	300	23	184	4673
5/64	2.0	150	18	47	1193	300	22.5	124	3149
3/32	2.4	200	17	40	1016	350	22	93	2410

FIGURE 6-78 Welding current range for flux-cored electrodes.

Tips for Using the Process

These tips are essentially the same as those given for gas metal arc welding. There is only one major difference; the slag covering on the weld deposit allows the possibility of slag entrapment with flux-cored arc welding. This requires manipulation of the welding arc in the same manner as used with shielded metal arc welding to avoid flux entrapment. The electrode should be directed toward the leading edge of the weld puddle and the tip-to-work or stickout length should be kept uniform. Special guns are available which incorporate electrical stickout, and these increase deposition rates. However, penetration is reduced and therefore the proper current and voltage should be employed to ensure root penetration.

Safety Considerations

Safety considerations for flux-cored arc welding are the same as those for the other arc welding processes, and this was completely covered in Chapter 3. One safety factor in flux-cored arc welding is the amount of smoke and fumes produced. This process produces more smoke than shielded metal arc welding with covered electrodes; however, much more weld metal is being deposited per hour with this process. Proper positioning of the welder's head and the use of curved front welding hoods will greatly reduce the smoke that will reach the breathing zone. For more efficient collection of smoke, exhaust welding guns are recommended.

Limitations of the Process

The following are some of the limitations to this process:

- Flux-cored arc welding is used only to weld ferrous metals, primarily steels.
- The process normally produces a slag covering that must be removed.
- Flux-cored electrode wire is more expensive on a weight basis than are solid electrode wires.
- The equipment is more expensive and complex than required for shielded metal arc welding; however, the increased productivity compensates for this.

For the gas-shielded version, the external shield may be adversely affected by breezes and drafts. This is also true in the self-shielding version, but to a lesser degree.

Industrial Use and Typical Applications

The flux-cored arc welding process is replacing shielded metal arc for many applications, replacing gas metal arc welding, primarily the CO_2 version, and replacing submerged arc welding for thinner metal.

The construction equipment industry has used the process to the greatest degree. Figure 6-79 shows the application of the process on a scraper blade, which is quite typical; however, frames and other weldments utilize the process.

The industrial equipment industry that produces machine tool bases, press frames, and so on, also is a large user of FCAW. A typical application on a press frame is shown in Figure 6-80. This type of work involves relatively heavy plate fabrication, usually carbon or low-alloy steel.

The tank and vessel industry also utilizes flux-cored arc welding. The process has qualified to the requirements of ASME for pressure vessel work. It is used on many applications that conform to the code. Figure 6-81 shows a typical vessel being welded.

The structural steel industry has switched almost entirely to flux-cored arc welding, both for in-plant fabrication and for erection work. For the erection of structural steel it is particulary useful for column splices, beam splices, and beam-to-column connections. Figure 6-82

FIGURE 6-79 Welding scraper blade.

FIGURE 6-80 Welding press frame.

FIGURE 6-81 Welding pressure vessel.

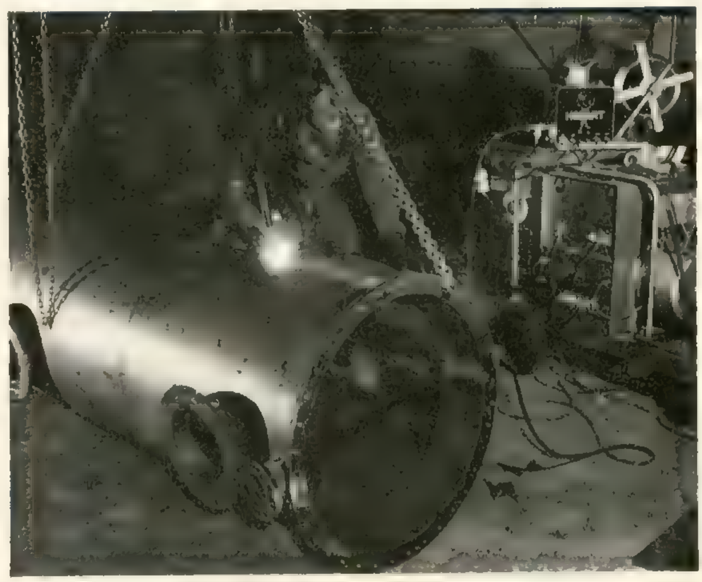
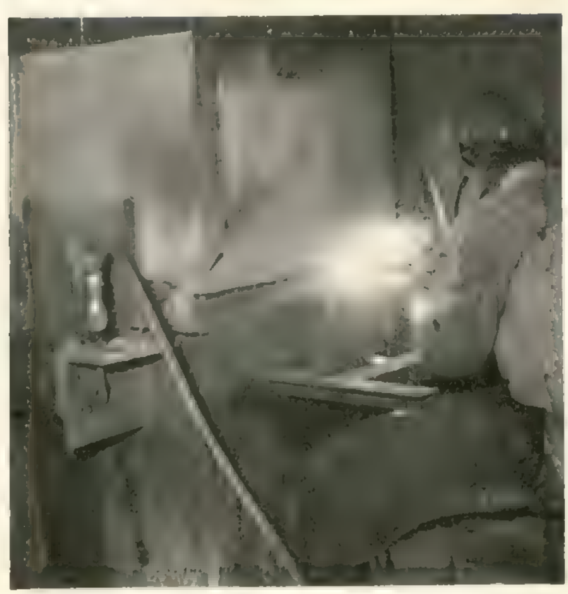


FIGURE 6-82 Welding box column splice.



shows a typical heavy box column being welded with the flux-cored welding process.

The piping industry uses flux-cored arc welding with the smaller-diameter electrode wires that provide all-position capabilities.

The flux-cored arc welding process is gaining in popularity because of its proven economies. Flux-cored arc welding provides high deposition rates. It provides a higher operator factor or duty cycle. The electrode wires have a higher rate of utilization, and more economical weld joint details can be employed. This results in lower-cost overall weldment production, which is the continual goal for weldment fabricators.

6-6 SUBMERGED ARC WELDING

Submerged arc welding (SAW) is an arc welding process that uses an arc between a bare metal electrode and the weld pool. The arc and molten metal are shielded by a blanket of granular flux on the workpieces. The process is used without pressure and with the filler metal from an electrode, and sometimes from a supplemental source such as a welding rod, flux, or flux with metal granules.

Principles of Operation

The submerged arc welding process (Figure 6-83) utilizes the heat of an arc between a continuously fed electrode and the work. The heat of the arc melts the surface of the base metal and the end of the electrode. The metal melted off the electrode is transferred through the arc to the workpiece, where it becomes the deposited weld metal. Shielding is obtained from a blanket of granular flux, which is laid directly over the weld area. The flux close to the arc melts and intermixes with the molten weld metal and helps purify and fortify it. The flux forms a glass-like slag that is lighter in weight than the deposited weld metal and floats on the surface as a protective cover. The weld is submerged under this layer of flux and slag—hence the name "submerged arc welding." In Europe it is called "welding under powder," The welder's view is shown in Figure 6-84. The flux and slag normally cover the arc so that it is not visible. The unmelted portion of the flux can be reused. The electrode is fed into the arc automatically from a coil. The arc is maintained automatically and travel can be manual or by machine. The arc is initiated by a fuse-type start or by a reversing or retrack system. The metal transfer mode is less important in submerged arc welding.

FIGURE 6-83 Process diagram (SAW).

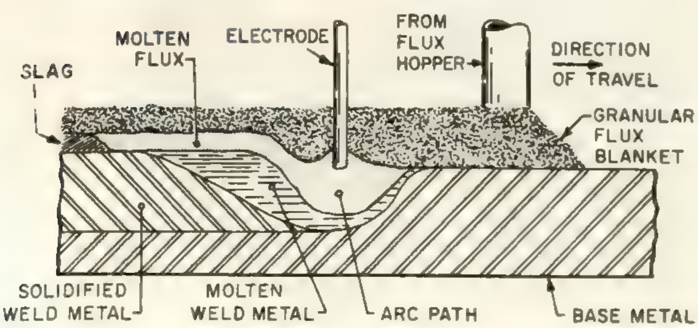


FIGURE 6-84 Welder's view of submerged arc welding.

Advantages and Major Uses

The submerged arc welding process, introduced in the early 1930s, is one of the older automatic processes and was originally used to make the longitudinal seam in large pipe. It was developed to provide high-quality deposited weld metal by shielding the arc and the molten metal from the cantaminating effects of the air. The major advantages of the process are:

- High quality weld metal
- Extremely high deposition rate and speed
- Smooth, uniform finished weld with no spatter
- Little or no smoke
- No arc flash, thus minimal need for protective clothing
- High utilization of electrode wire
- Easily automated for high operator factor
- Manipulative skills normally not involved

The submerged arc process is widely used in heavy steel plate fabrication work. This includes the welding of structural shapes, the longitudinal seam of larger diameter

pipe, the manufacture of machine components for all types of heavy industry, the manufacture of vessels and tanks for pressure and storage use. It is widely used in the shipbuilding industry for splicing and fabricating subassemblies, and by many other industries where steels are used in medium to heavy thickness. It is also used for surfacing and buildup work, maintenance, and repair.

Methods of Application and Position Capabilities

The most popular method of applying is the machine method where the operator monitors the welding operation. Second in popularity is the automatic method, where welding is a pushbutton operation. The process can be applied semiautomatically; however, this method of application is not too popular. The process cannot be applied manually because it is impossible for a welder to control an arc that is not visible.

The submerged arc welding process is a limited-position welding process. Welding can be done in the flat position and in the horizontal fillet postion with ease. The welding positions are limited because of the large pool of molten metal which is very fluid and the slag is also very fluid and will tend to run out of the joint. Under special controlled procedures it is possible to weld in the horizontal position, sometimes called 3-o'clock welding. This requires special devices to hold the flux up so that the molten slag and weld metal cannot run away. The process is not used in the vertical or overhead position.

Weldable Metals and Thickness Range

Submerged arc welding is used to weld low- and medium-carbon steels, low-alloy high-strength steels, quenched and tempered steels, and many stainless steels. Experimentally it has been used to weld certain copper alloys, nickel alloys, and even uranium. This information is summarized in Figure 6-85. Submerged arc welding is also used for hard surfacing and overlay operations.

Metal thickness from $\frac{1}{16}$ in. (1.6 mm) to $\frac{1}{2}$ in. (12 mm) can be welded with no edge preparation. With edge preparation welds can be made with a single pass on material from $\frac{1}{4}$ in. (6.4 mm) through 1 in. (25 mm). When multipass technique is used, the maximum thickness is practically unlimited. (Figure 6-86).

Base Metal	Weldability
Wrought iron	Weldable
Low carbon steel	Weldable
Low alloy steel	Weldable
High and medium carbon	Possible but not popular
Alloys steel	Possible but not popular
Stainless steel	Weldable

FIGURE 6-85 Metals weldable (SAW).

Horizontal fillet welds can be made up to $\frac{3}{8}$ in. (9.5 mm) in a single pass and in the flat position fillet welds can be made up to 1 in. (25 mm) size.

Joint Design

The submerged arc welding process can utilize the same joint design details as the shielded metal arc welding process. These joint details are given in Chapter 19. However, for maximum utilization and efficiency of submerged arc welding, different joint details are suggested.

For groove welds, the square groove design can be used up to a $\frac{5}{8}$-in. (16-mm) thickness. Beyond this thickness bevels are required. Open roots are used but backing bars are necessary since the molten metal will run through the joint. When welding thicker metal, if a sufficiently large root face is used, the backing bar may be eliminated. However, to assure full penetration when welding from one side, backing bars are recommended. Where both sides are accessible, the backing weld can be made which will fuse into the original weld to provide full penetration. Recommended submerged arc joint designs are shown in Figure 6-87.

Welding Circuit and Current

The welding circuit employed for single-electrode submerged arc welding (Figure 6-88) requires a wire feeder system and a power supply.

The submerged arc welding process uses either direct or alternating current for welding power. Direct current is used for most applications that employ a single arc. Both direct-current electrode positive (DCEP) and electrode negative (DCEN) are used.

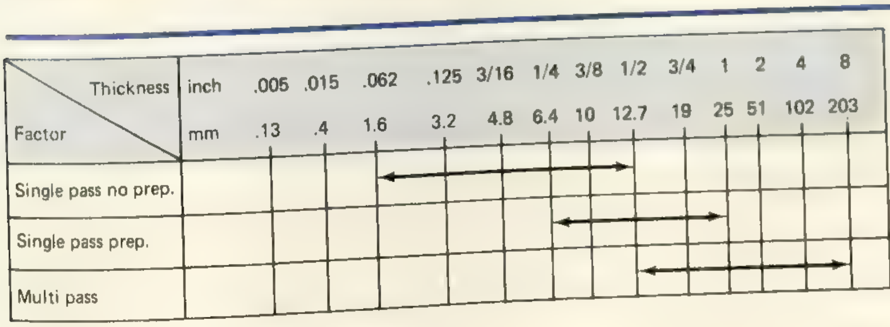


FIGURE 6-86 Base metal thickness range (SAW).

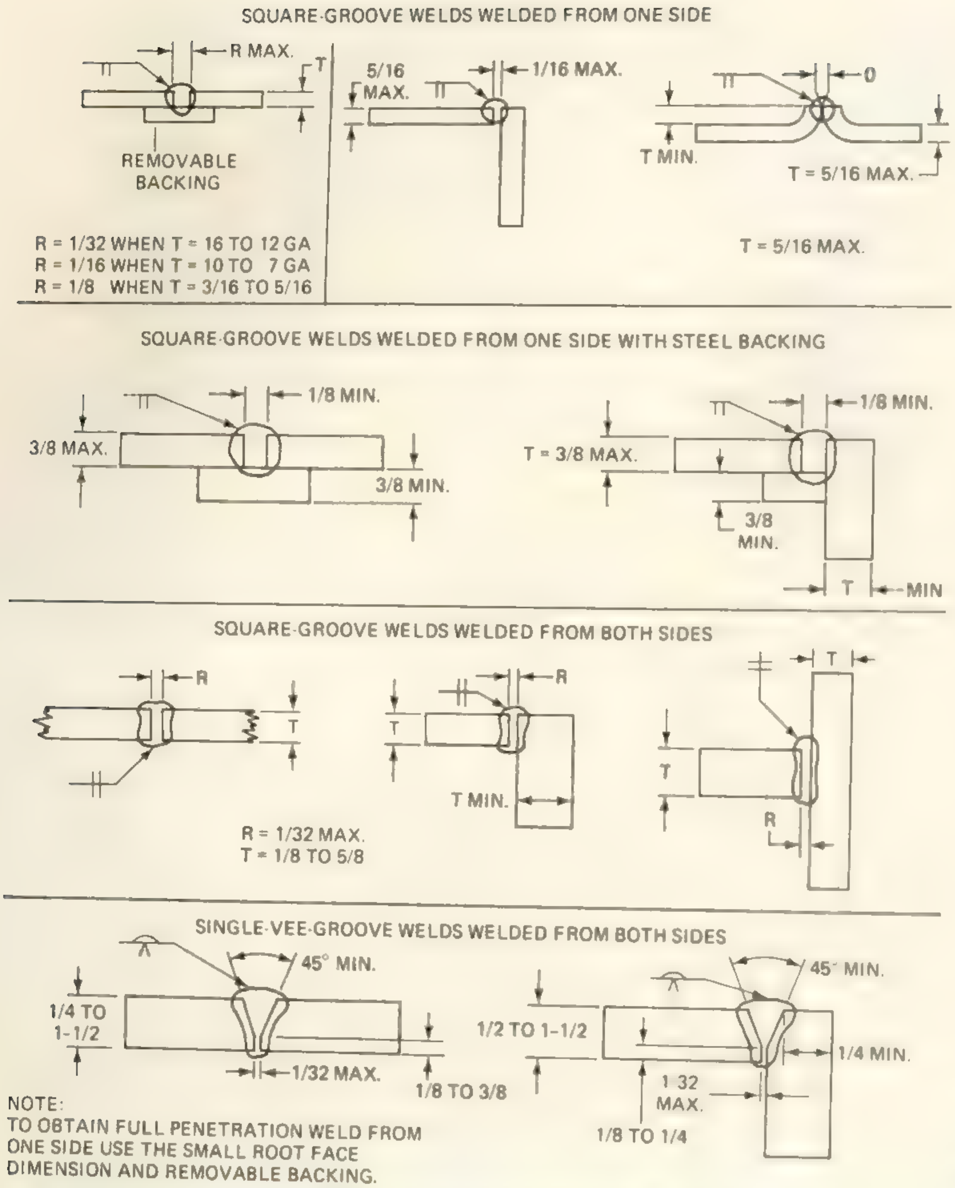


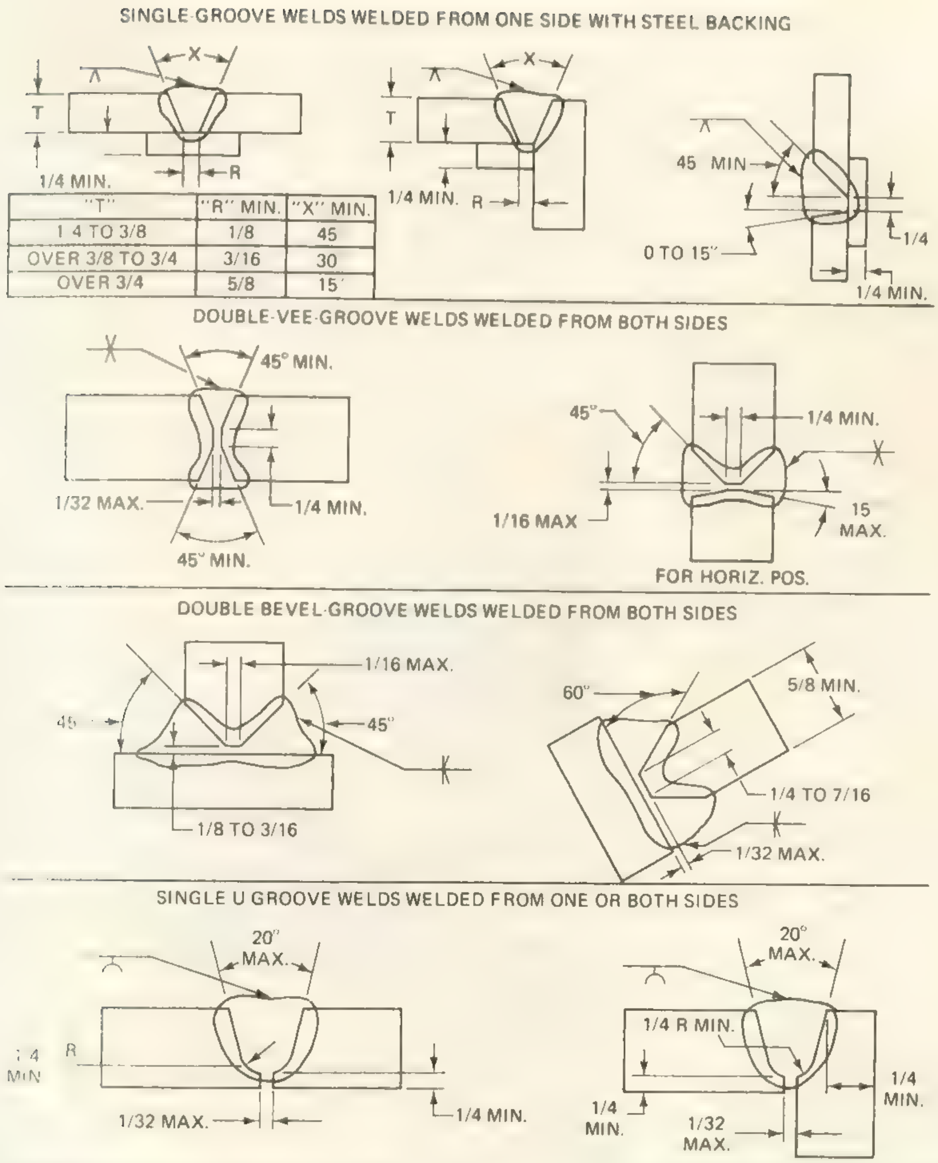
FIGURE 6-87 Weld joint designs (SAW).

The constant-voltage type of direct-current power is more popular for submerged arc welding with ⅛ in. (3.2 mm) and smaller-diameter electrode wires. The constant-current power system is normally used for welding with 5/32-in. (4-mm) and large-diameter electrode wires. The control circuit for CC power is more complex since it duplicates the actions of the welder to retain a specific arc length. The wire feed system must sense the voltage across the arc and feed the electrode wire into the arc to maintain this voltage. As conditions change, the wire feed must slow down or speed up to maintain the prefixed voltage across the arc. This adds complexity to the control system and the system cannot react instantaneously. Arc starting is more complicated with the constant current system since it requires the use of a reversing system to strike the arc, retract, and then maintain the preset arc voltage.

For ac welding the constant-current power is always used. When multiple-electrode-wire systems are used with both ac and dc arcs, the constant-current power system is utilized. The constant-voltage system, however, can be applied when two wires are fed into the arc supplied by a single power source. Welding current for submerged arc welding can vary from as low as 50 A to as high as 2000 A. Most submerged arc welding is done in the range 200 to 1200 A.

Equipment Required to Operate

The equipment components required for submerged arc welding (Figure 6-88) consist of (1) welding machine or power source, (2) the wire feeder and control system, (3) the welding torch for automatic welding, or the welding gun and cable assembly for semiautomatic welding, (4)



"T"	"R" MIN.	"X" MIN.
1/4 TO 3/8	1/8	45
OVER 3/8 TO 3/4	3/16	30
OVER 3/4	5/8	15°

FIGURE 6-87 *(cont.)*

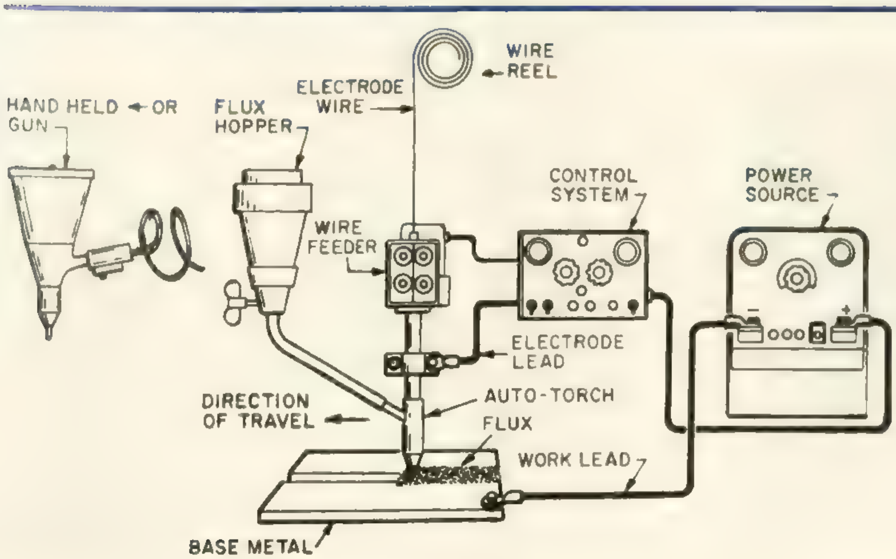


FIGURE 6-88 Circuit diagram (SAW).

the flux hopper and feeding mechanism and usually a flux recovery system, and (5) travel mechanism for automatic welding.

The power source for submerged arc welding must be rated for a 100% duty cycle, since the submerged arc welding operations are continuous and the length of time for making a weld may exceed 10 minutes. If a 60% duty cycle power source is used, it must be derated according to the duty cycle curve for 100% operation.

When constant current is used, either ac or dc, the voltage-sensing electrode wire feeder system must be used. The CV system is only used with direct current.

Both generator and transformer–rectifier power sources are used, but the rectifier machines are more popular. Welding machines for submerged arc welding range in size from 300 to 1500 A. They may be connected in parallel to provide extra power for high-current applications. Direct-current power is used for semiautomatic applications, but alternating-current power is used primarily with the machine or the automatic method. Multiple-electrode systems require specialized types of circuits, especially when ac is employed.

For semiautomatic application a welding gun and cable assembly are used to carry the electrode and current and to provide the flux at the arc. An application of semiautomatic submerged arc welding is shown in Figure 6-89. A small flux hopper is attached to the end of the cable assembly and the electrode wire is fed through the bottom of this flux hopper through a current pickup tip to the arc. The flux is fed from the hopper to the welding area by means of gravity. The amount of flux fed depends on the height the gun is held above the work. The hopper gun may include a start switch to initiate the weld, or it may utilize a "hot" electrode so that when the electrode is touched to the work feeding will begin automatically. Pressure flux feed systems are also used.

For automatic welding, the torch is normally attached to the wire feed motor and the flux hopper is attached to the torch. The flux hopper may have a magnetically operated valve that can be opened or closed by the control system.

The final piece of equipment sometimes used is a travel carriage, which can be a simple tractor or a complex moving specialized fixture. A typical travel carriage is shown in Figure 6-90. A flux recovery unit can be provided to collect the unused submerged arc flux and return it to the supply hopper. Submerged arc welding systems can become more complex by adding such devices as seam followers, weavers, or work movers.

FIGURE 6-89 Semiautomatic submerged arc welding.

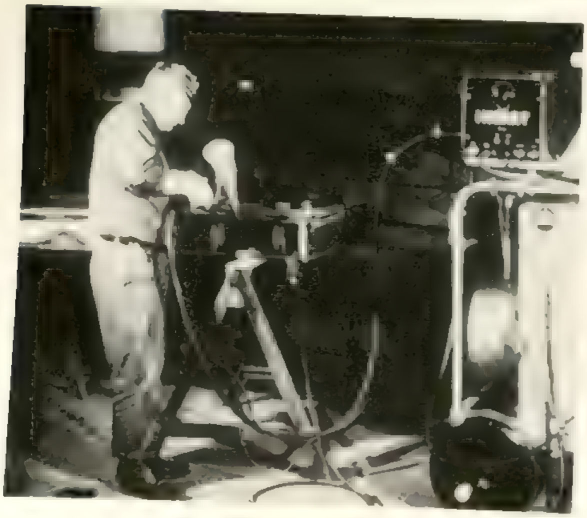
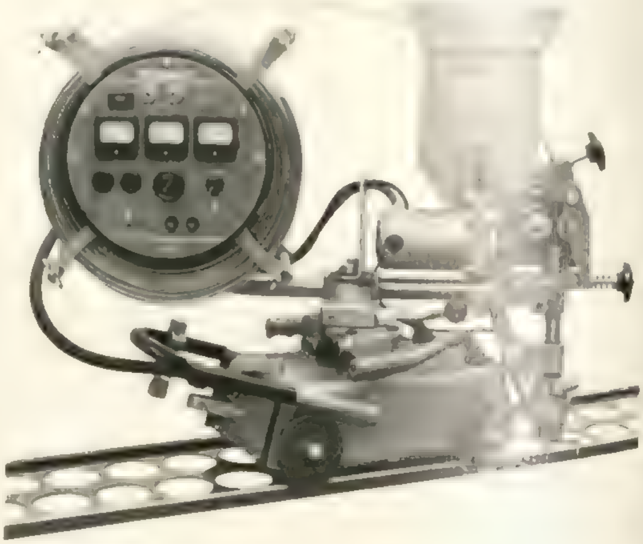


FIGURE 6-90 Submerged arc head on travel carriage.



Materials Used

Two materials are used in submerged arc welding, the welding flux and the consumable electrode. The Welding Society has two specifications,[21, 22] which provide a classification system that includes both the flux and the electrode. The flux is specified by the letter F followed by a two- or three-digit number that indicates the minimum tensile strength in increments of 10,000 psi. This is followed by a letter which indicates the condition of heat treatment for testing the welds. "A" stands for "as welded," and "P" stands for "postweld heat treated." This is followed by a one-or two-digit number which indicates the minimum temperature in Fahrenheit of impact tests to provide 20 ft-lb of energy absorption (or the minimum temperature in Celsius of an impact test to provide 27 joule of energy absorption). There are eight classifications for impact strength. The classification for the flux is summarized in Figure 6-91.

The electrode is specified by the letter E followed by three digits. Note, however, that the letter E can be

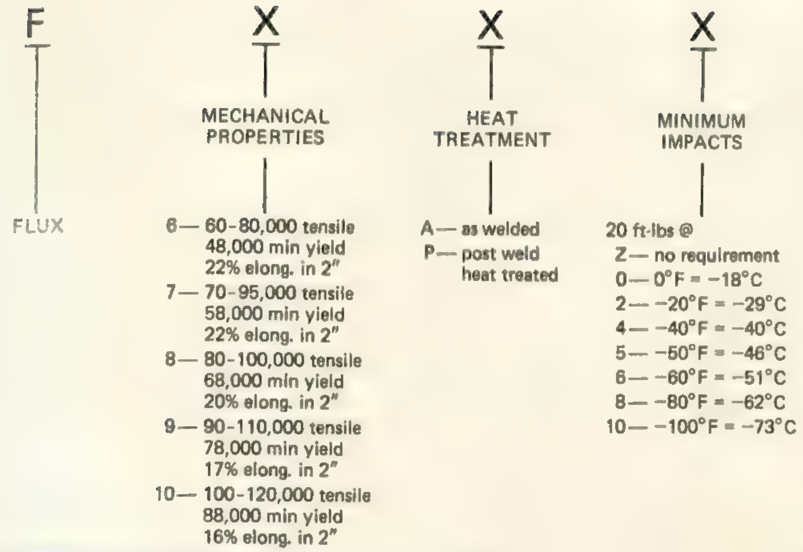


FIGURE 6-91 Submerged arc flux classification system.

followed by the letter C if the electrode is of composite construction. Omission of a C indicates a solid electrode. The next digit is to designate the manganese content. This is followed by a one- or two-digit number used to indicate nominal carbon content in hundredths of a percent carbon. These digits are sometimes followed by a letter K which indicates that the electrode steel was silicon killed. If the steel is of another type, a K will not appear. This is sometimes followed by two digits which indicate the alloys that are present. Figure 6-92 shows the electrode classification system for carbon steels.[21] This does not, however, cover the alloy steels. For complete information on the alloy steels, refer to the AWS Specification.[22] The composition requirements for submerged arc carbon steel electrodes are shown in Figure 6-93.

An example of the flux–electrode classification system is as follows:

> *F7A6-EM12K:* indicates a flux–electrode combination that will produce weld metal which in the as-welded condition will have a tensile strength of not less than 70,000 psi and a Charpy V-notch impact strength of at least 20 ft-lb at-60 °F when deposited with an EM12K electrode under standard conditions called for in the AWS specification.

The flux shields the arc and molten weld metal from atmospheric oxygen and nitrogen. The flux contains deoxidizers and scavengers, which help remove impurities from the weld metal. Flux also provides a means for introducing alloys into the weld metal. Alloys and deoxidizers may also be introduced from the welding electrode.

As the molten flux cools, it forms a glassy slag covering, which protects the surface of the weld during cooling. The nonmelted portion of the flux does not change its form; its properties are not affected, so this unmelted flux can be recovered and reused. The flux that melts and forms the slag covering must be removed from the weld. This is easily done after the weld cools, and in many cases will peel for removal without special effort. In a groove weld the solidified slag may have to be removed by a chipping hammer. The fused flux that is removed must be discarded since the alloying elements and deoxidizers are exhausted during the melting phase.

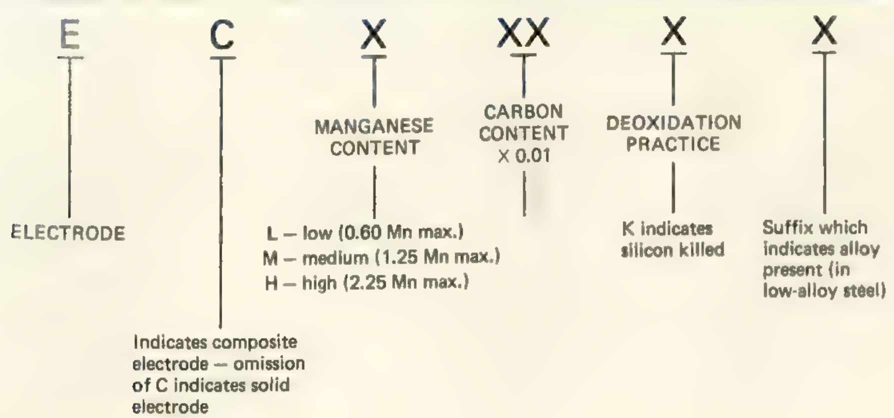


FIGURE 6-92 Electrode classification system. (See Ref. 22 for low-alloy steels.)

Electrode Classification	CHEMICAL COMPOSITION (WT %) [a,b] C	Mn	Si	S	P	Cu[c]
	Low-manganese steel electrodes					
EL8	0.10	0.25/0.60	0.07	0.035	0.035	0.35
EL8K	0.10	0.25/0.60	0.10/0.25	0.035	0.035	0.35
EL12	0.05/0.15	0.25/0.60	0.07	0.035	0.035	0.35
	Medium-manganese steel electrodes					
EM12	0.06/0.15	0.80/1.25	0.10	0.035	0.035	0.35
EM12K	0.05/0.15	0.80/1.25	0.10/0.35	0.035	0.035	0.35
EM13K	0.07/0.19	0.90/1.40	0.35/0.75	0.035	0.035	0.35
EM15K	0.10/0.20	0.80/1.25	0.10/0.35	0.035	0.035	0.35
	High-manganese steel electrodes					
EH14	0.10/0.20	1.70/2.20	0.10	0.035	0.035	0.35

[a] Single values are maximums.
[b] Electrodes shall be analyzed for those elements for which specific values are shown. Elements other than those shown, which are intentionally added (except iron), shall also be reported. The total of these latter elements and all other elements not intentionally added shall not exceed 0.50%.
[c] The copper limit includes any copper coating that may be applied to the electrode.

FIGURE 6-93 Electrode composition. (See Ref. 22 for low-alloy steels.)

Selection of Flux Wire Combination

In submerged arc welding it is necessary to select electrode and flux combination to match the base metal composition and properties. Fluxes of different manufacturers are not interchangeable without making tests. Fluxes may be neutral or active. Neutral fluxes will not produce any significant changes in weld metal chemistry. They are normally used for multipass welding. Active fluxes contain small amounts of manganese and/or silicon used to reduce porosity and weld cracking. They are normally used for single-pass applications. The third type are alloy fluxes, which when used with plain carbon steel electrodes produce alloy weld deposits. This is done to match particular base metals or with additional alloys is used for hardfacing applications.

Variations in arc voltage change flux consumption. Higher are voltage (long arc length) increases the amount of flux melted or consumed. This can cause more alloy to be deposited; hence it is important to follow the manufacturer's recommended voltages when using a particular flux.

In general, the flux is selected based on the mechanical properties required of the weld deposit. The electrode would be selected in conjunction with the flux to deliver these mechanical properties. Manufacturers usually list fluxes with several combinations of electrodes for welding different steels. The manufacturer's recommendations should be followed with respect to single- or multiple-pass type of application related to the base metal properties. If weld requirements are critical, tests should be made to qualify the procedure that will produce the weld properties desired.

Deposition Rates and Quality of Welds

The deposition rates of the submerged arc welding process are higher than any other arc welding process. Deposition rates for single electrodes are shown in Figure 6-94. There are four factors that control the deposition rate of submerged arc welding, polarity, long stickout, additives in the flux, and additional electrodes. The deposition rate is the highest for direct current electrode negative DCEN. The deposition rate for alternating current is between DCEP and DCEN. The polarity of maximum heat is the negative pole.

The deposition rate can be increased by extending the stickout. This is the distance from the point where current is introduced into the electrode to the arc. It is also called I^2R welding. Normally, the distance between the contact tip and the work is 1 to 1½ in. (25 to 38 mm). If the stickout is increased, it will cause preheating of the electrode wire which will greatly increase the deposition rate. As stickout is increased, the penetration into the base metal decreases. This factor must be given serious consideration because in some situations the penetration is required. The relationship between stickout and deposition rate is shown in Figure 6-95. The deposition rates can be increased by metal additives in the submerged arc flux. Additional electrodes can be used to increase the overall deposition rate.

The quality of the weld metal deposited by the

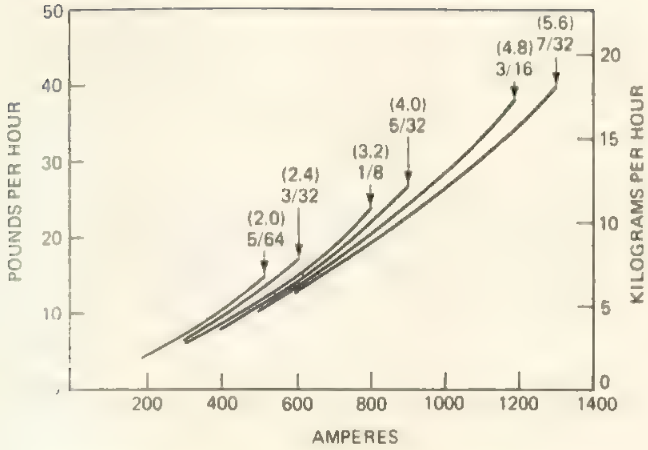
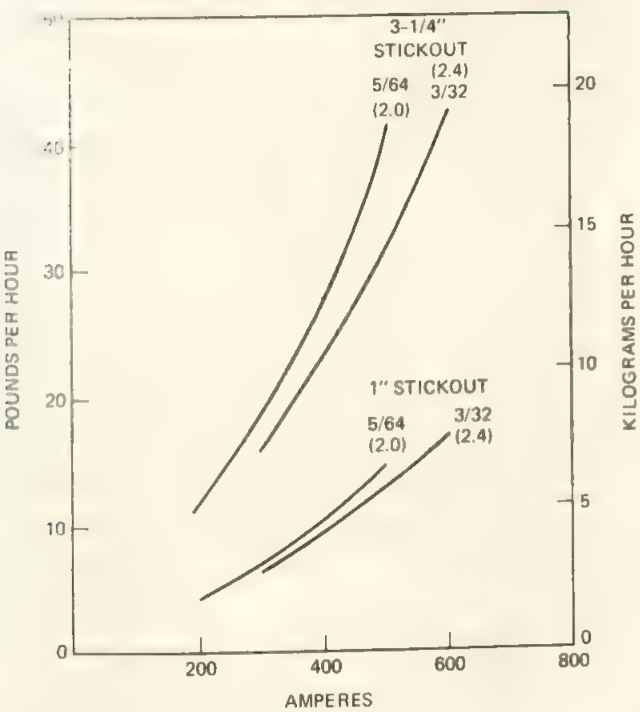


FIGURE 6-94 **Welding deposition rates (SAW).**

...merged arc welding process is high. The weld metal strength and ductility exceeds that of the mild steel or low-alloy base material when the correct combination of electrode wire and submerged arc flux is used. In general, the weld bead size per pass is much greater with submerged arc welding than with any of the other arc welding process. The heat input is higher and cooling rates are slower, and, for this reason, gases are allowed more time to escape. The submerged arc slag is lower in density than the weld metal, so it will float to the top of the weld.

FIGURE 6-95 **Stickout versus deposition rate.**



Uniformity and consistency are advantages of this process when applied automatically.

Several problems may occur when using the semiautomatic application method. The electrode wire may be curved when it leaves the nozzle of the welding gun. This curvature can cause the arc to be struck in a location not expected by the welder. When welding in fairly deep grooves, the curvature may cause the arc to be against one side of the weld joint rather than at the root. This will cause incomplete root fusion and flux will be trapped at the root of the weld. Another problem with semiautomatic welding is the problem of completely filling the weld groove or maintaining exact size, since the weld is hidden and cannot be observed while it is being made. This requires making an extra pass or in some cases too much weld is deposited. Variations in root opening affect the travel speed and if travel speed is uniform the weld may be under- or overfilled in different areas. High operator skill and experience will overcome this problem.

There is another quality problem associated with extremely large single-pass weld deposits. When these large welds solidify, the impurities in the melted base metal and in the weld metal all collect at the last point to freeze, which is the centerline of the weld. If there is sufficient restraint and enough impurities are collected at this point, centerline cracking may occur. This can happen when making large single-pass flat fillet welds if the base metal plates are 45° from flat. A simple solution is to avoid placing the parts at a true 45° angle. It should be varied approximately 10° so that the root of the joint is not in line with the centerline of the fillet weld. Another solution is to make multiple passes rather than attempting to make a large weld in a single pass.

Excessively hard weld deposits contribute to cracking of the weld during fabrication or during service. A maximum hardness level of 225 Brinell is recommended. The reason for the hard weld in carbon and low-alloy steels is too rapid cooling, inadequate postweld treatment, or excessive alloy pickup in the weld metal. Excessive alloy pickup is due to selecting an electrode that has too much alloy, or a flux that introduces too much alloy into the weld, or the use of excessively high welding voltages. Caution should be established to avoid these.

In automatic and machine welding defects may occur at the start or at the end of the weld. The best solution is to use runout tabs so that starts and stops will be on the tabs rather than on the product.

Weld Schedules

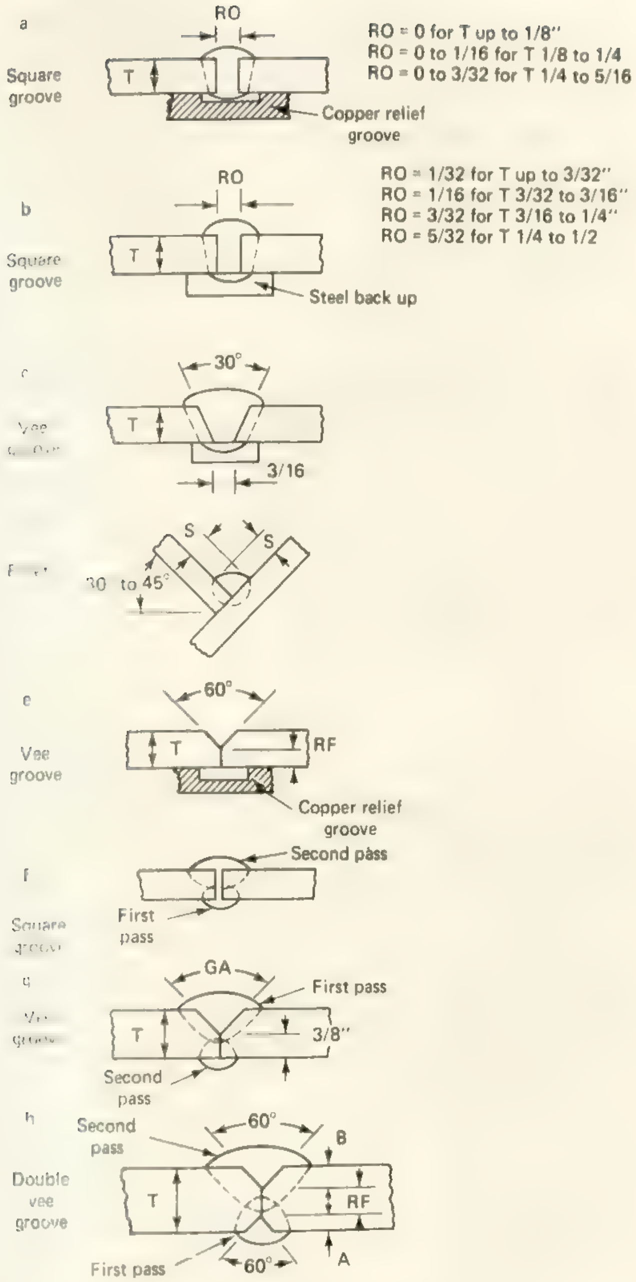
The submerged arc welding process applied by machine or fully automatically should be done in accordance with welding procedure schedules. Figure 6-96 shows the recommended welding schedules for submerged arc welding using a single electrode on mild and low-alloy steels. These tables can be used for welding other ferrous

materials, but were developed for mild steel. All of the welds made by this procedure should pass qualification tests, assuming that the correct electrode and flux have been selected. If the schedules are varied more than 10%, qualification tests should be performed to determine the weld quality.

FIGURE 6-96 Welding procedure schedules (SAW).

Material Thickness			Type of Weld	Electrode Dia. in.	Welding Current (A dc)	Arc Voltage (Elec. Pos.)	Wire Feed (in./min)	Travel Speed (in./min)
Ga	in.	mm						
16	0.063	1.6	a Square groove	3/32	300	22	68	100-140
			b Square groove	1/8	425	26	53	95-120
14	0.078	2	a Square groove	3/32	375	23	85	100-140
			b Square groove	1/8	500	27	65	75-85
12	0.109	2.8	a Square groove	1/8	400	23	51	70-90
			b Square groove	1/8	550	27	65	50-60
			d Fillet	1/8	400	25	51	40-60
10	0.140	3.5	a Square groove	1/8	425	26	53	50-80
			b Square goove	5/32	650	27	55	40-45
3/16	0.188	4.8	a Square groove	5/32	600	26	50	40-75
			b Square groove	3/16	875	31	55	35-40
			d Fillet	1/8	525	26	67	35-40
1/4	0.250	6.3	a Square goove	3/16	800	28	50	30-35
			b Square groove	3/16	875	31	56	22-25
			d Fillet	5/32	650	28	56	30-35
			e V groove	3/16	750	30	47	25-40
3/8	0.375	9.5	b Square groove	3/16	950	32	61	20-25
			f Square groove	3/16	1st pass 500	32	27	30
					2nd pass 750	33	47	30
			e V groove	3/16	900	33	57	23-25
			d Fillet	3/16	950	31	61	30-35
1/2	0.500	12.6	c V groove	3/16	975	33	63	12-17
			f Square groove	3/16	1st pass 650	34	40	25
					2nd pass 850	35	54	23-27
			e V groove	3/16	950	35	61	18-20
			d Fillet	3/16	950	33	61	14-17
3/4	0.750	19	c V groove	7/32	1000	35	49	68
			f Square groove	3/16	1st pass 925	37	59	12
					2nd pass 1000	40	65	11
			e V groove	7/32	950	36	46	10-12
			d Fillet	7/32	1000	35	49	6-8
			g V groove	7/32	1st pass 950	34	46	15
					2nd pass 750	34	25	22
			h Double V groove	3/16	1st pass 700	35	42	20-22
					2nd pass 1000	36	65	14-16
1	1.000	25.4	g V groove	7/32	1st pass 1150	36	58	11
					2nd pass 850	36	40	20
			h Double V groove	7/32	1st pass 900	36	42	13-15
					2nd pass 1075	36	52	12-14
1¼	1.25	32	h Double V groove	7/32	1st pass 1000	36	50	13
					2nd pass 1125	37	56	8
1½	1.50	38	h Double V groove	7/32	1st pass 1050	36	51	9
					2nd pass 1125	37	56	7

(a)



(b)

FIGURE 6-96 *(cont.)*

Welding Variables

The welding variables for submerged arc welding are much similar to the other arc welding processes, with several exceptions. The variables will be coverd later in this chapter.

In submerged arc welding the electrode type and the flux type are based on the mechanical properties required by the weld. The electrode size is related to the weld joint size and the current recommended for the particular joint. This must also be considered in determining the number of passes or beads for a particular joint. Welds for the same joint dimension can be made with many or few passes; this depends on the weld metal metallurgy desired. Multiple passes are more expensive but usually deposit higher-quality weld metal. The polarity is established initially and is based on whether maximum penetration or maximum deposition rate is required.

The major variables that affect the weld involve heat input and include the welding current, the arc voltage, and the travel speed. Welding current is the most important. For single-pass welds the current should be sufficient for the desired penetration without burn-through. The higher the current, the deeper the penetration. In multipass work the current should be suitable to produce the size of the weld expected in each pass. The welding current should be selected based on the electrode size.

The arc voltage is varied within narrow limits. It has an influence on the bead width and shape. Higher voltages will cause the bead to be wider and flatter. Extremely high arc voltage should be avoided since it can cause cracking. This is because an abnormal amount of flux is melted and excess deoxidizers may be transferred to the weld deposit lowering its ductility. Higher arc voltage also increases the amount of flux consumed. The low arc voltage produces a stiffer arc that improves penetration, particularly in the bottom of deep groves. If the voltage is too low, a very narrow bead will result. It will have a high crown and the slag will be difficult to remove.

Travel speed has an influence on both bead width and on penetration. Faster travel speeds produce narrower beads that have less penetration. This can be an advantage for sheet metal welding, where small beads and minimum penetration are required. If speeds are too fast, however, there is a tendency for undercut and porosity, since the weld freezes quicker. If the travel speed is too slow, the electrode stays in the weld puddle too long which will create poor bead shape and may cause excessive spatter and flash through the layer of flux.

The secondary variables include the angle of the electrode to the work, the angle of the work itself, the thickness of the flux layer, and, most important, the distance between the current pickup tip and the arc. The latter factor, called electrode stickout, was discussed previously.

The depth of the flux layer must be considered. If it is too thin, there will be too much arcing through the flux or arc flash. This also may cause porosity. If the flux depth is too heavy, the weld may be narrow and humped. On the subject of flux, too many fines (small particles of flux) in the flux can cause surface pitting since the gases generated in the weld may not be allowed to escape. These are sometimes called *pock marks* on the bead surface.

Tips for Using the Process

One of the major applications for submerged arc welding is on circular welds where the parts are rotated under a fixed head. These welds can be made on the inside or outside diameter. Submerged arc welding produces a large molten weld puddle and molten slag which tends to run. This dictates that on outside diameters the electrode should be positioned ahead of the extreme top, or 12-o'clock position, so that the weld metal will begin to solidify before it starts the downside slope. This becomes more of a problem as the diameter of the part being welded is smaller. Improper electrode position will increase the possibility of slag entrapment or a poor weld surface. The angle of the electrode should also be changed and pointed in the direction of travel of the rotating part. When the welding is done on the inside circumference the electrode should be angled so that it is ahead of bottom center, or the 6-o'clock position. Figure 6-97 illustrates these two conditions.

Sometimes the work being welded is sloped downhill or uphill to provide different types of weld bead contours. If the work is sloped downhill, the bead will have less penetration and will be wider. If the weld is sloped uphill, the bead will have deeper penetration and will be narrower. These are based on all other factors remaining the same (Figure 6-98).

The weld will be different depending on the angle of the electrode with respect to the work when the work is level. This is the travel angle, which can be a drag or push angle, and has a definite effect on the bead contour and weld metal penetration. Figure 6-99 shows the relationship.

One-side welding with complete root penetration can be obtained with submerged arc welding. When the weld joint is designed with a tight root opening and with a fairly large root face, high current and electrode positive should be used. If the joint is designed with a root opening and a minimum root face, it will be necessary to use a backing bar since there will be nothing to support the molten weld metal. The molten flux is very fluid and will run through narrow openings. If this happens, the weld metal will follow and the weld will burn through the joint. Backing bars are needed whenever there is a root opening and a minimum root face.

Copper backing bars are useful when welding thin steel. Without backing bars, the weld would tend to melt through and the weld metal would fall away from the

FIGURE 6-97 Welding on rotating circular parts.

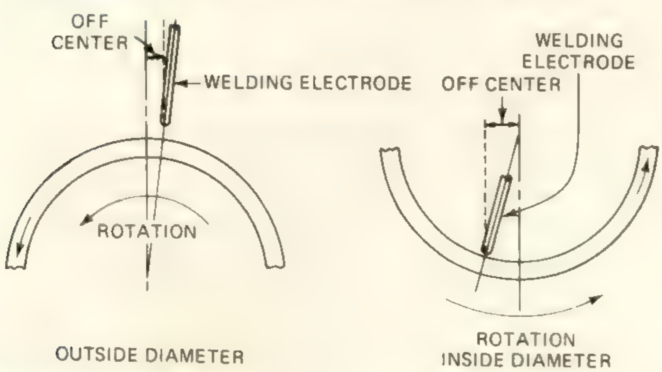


FIGURE 6-98 Angle of slope of work versus weld.

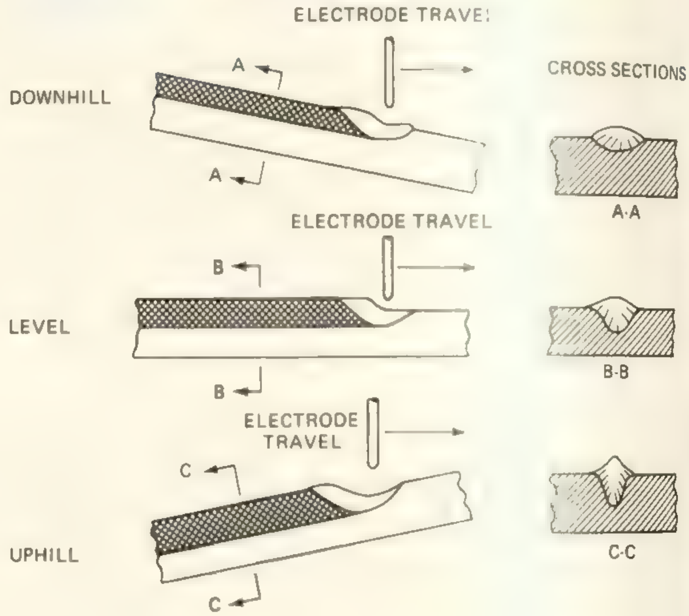
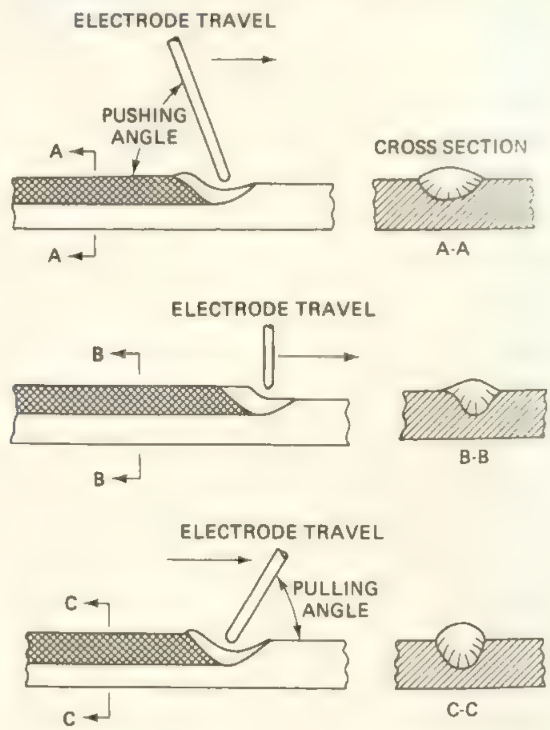


FIGURE 6-99 Angle of electrode versus weld



joint. The backing bar holds the weld metal in place until it solidifies. The copper backing bars may be water cooled to avoid the possibility of melting and copper pickup in the weld metal. For thicker materials, the backing may be submerged arc flux or other specialized type flux. More details of one-side welding are given in Chapter 26.

Safety Considerations

Safety precautions for submerged arc welding are somewhat fewer and less exacting than for other arc welding processes, because of the nature of the submerged arc process and because most submerged arc welding is applied automatically. See Chapter 3 for details.

The welding arc is normally not visible in the submerged arc welding process. Only small amounts of sparks or flash are produced; therefore, it is not necessary to wear a welding face helmet. It is necessary to wear tinted safety glasses.

Limitations of the Process

A major limitation of submerged arc welding is its limited welding positions capability. The other limitation is that it is used primarily to weld steels.

The high-heat input, slow-cooling cycle can be a problem when welding quenched and tempered steels. The heat input limitation of the steel in question must be strictly adhered to when using submerged arc welding. This may require the making of multipass welds where a single pass weld would be acceptable in mild steel. In some cases, the economics may be reduced to the point where flux-cored arc welding or some other process should be considered.

In semiautomatic submerged arc welding, the inability to see the arc and puddle can be a disadvantage in reaching the root of a groove weld and properly filling or sizing.

Variations of the Process

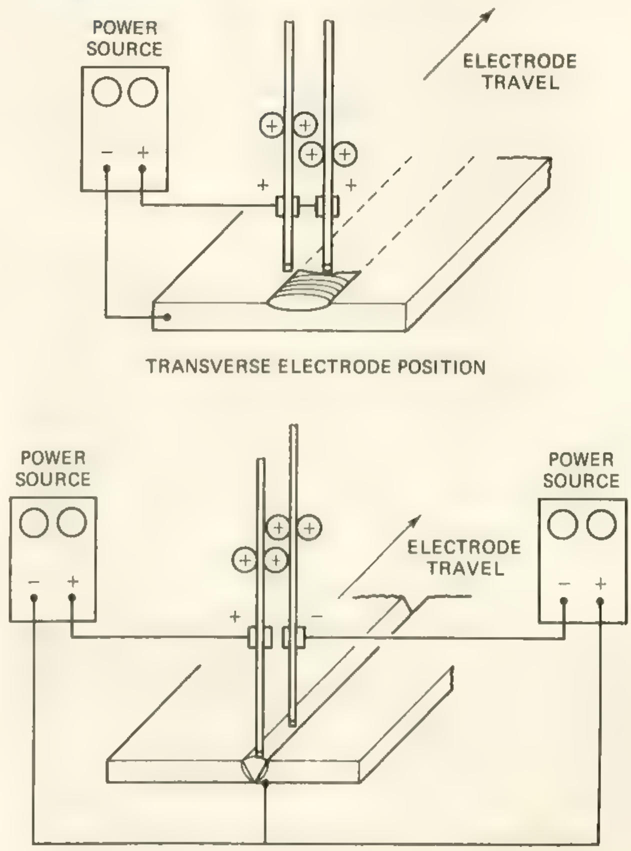
There are a large number of variations to the process that give it additional capabilities. Some of the more popular variations are:

1. Two-wire systems having the same power source
2. Two-wire systems having a separate power source
3. Three-wire system having a separate power source
4. Strip electrode for surfacing
5. Iron powder additions to the flux
6. Long-stickout welding (mentioned previously)
7. Electrically "cold" filler wire

The multiwire systems offer advantages since deposition rates and travel speeds can be improved by using more electrodes. Figure 6-100 shows the two methods of utilizing two electrodes, one with a single-power source and one with two-power sources. When a single-power source is used, the same drive rolls are used for feeding both electrodes into the weld. When two power sources are used, individual wire feeders must be used to provide electrical insulation between the two electrodes. With two electrodes and separate power it is possible to utilize different polarities on the two electrodes or to utilize alternating current on one and direct current on the other. The electrodes can be placed side by side, in what is called *transverse electrode position*, or they can be placed one in front of the other in the *tandem electrode position*.

The two-wire tandem electrode position with individual power sources is used where extreme penetration is required. The leading electrode is positive with the trailing electrode negative. The first electrode creates a digging action and the second electrode will fill the weld joint. When two dc arcs are in close proximity, there is a tendency for arc interference between them. In some cases, the second electrode is connected to alternating current to avoid the interaction of the arc. The three-wire

FIGURE 6-100 Two-electrode wire systems.



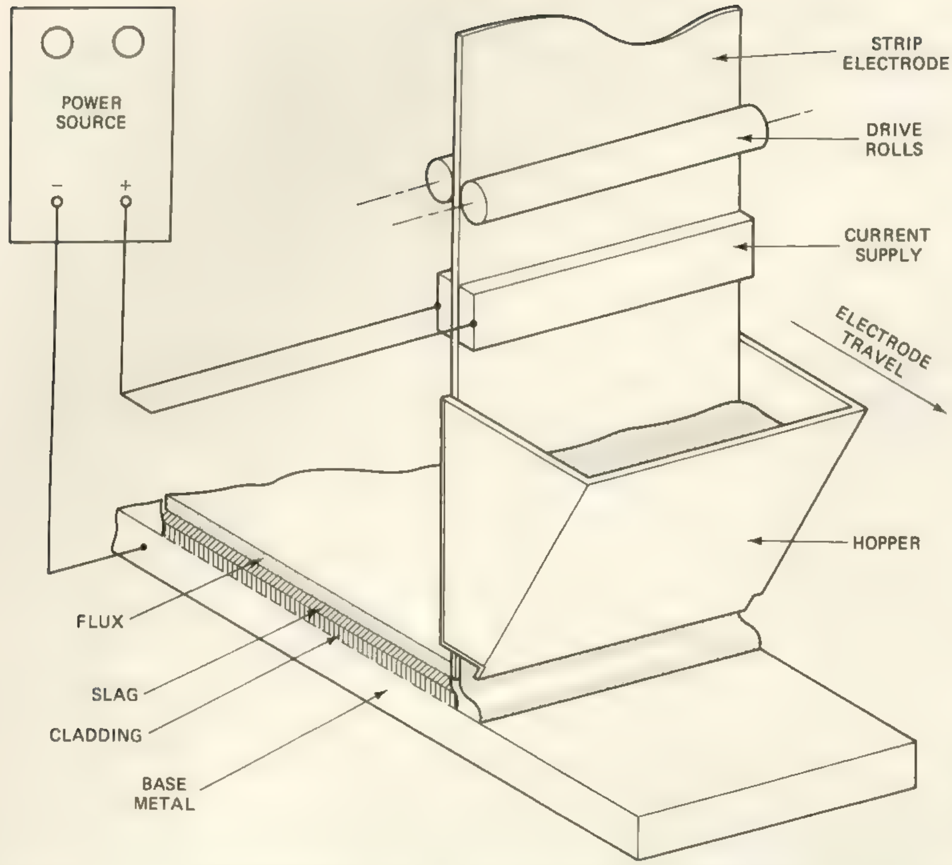


FIGURE 6-101 Strip electrode surfacing (SAW).

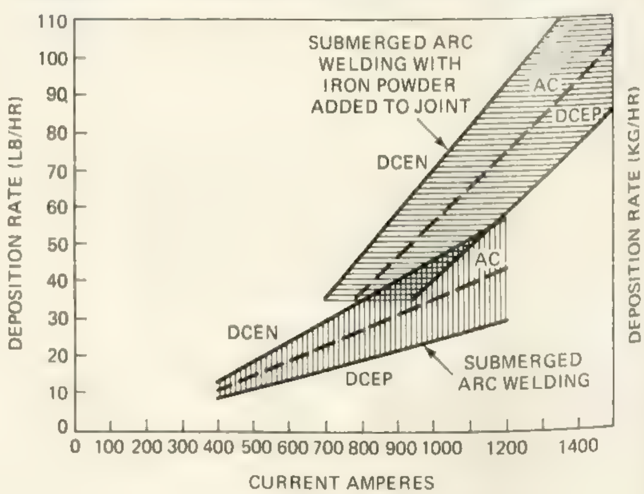
tandem system normally uses ac power on all three electrodes connected to three-phase power systems. The three-wire systems are used for making high-speed longitudinal seams for large-diameter pipe and for fabricated beams. Extremely high currents can be used, with correspondingly high travel speeds and deposition rates.

The strip welding system is used to overlay mild and alloy steels, usually with stainless steel. A wide bead is produced that has a uniform and minimum penetration. This process variation is shown in Figure 6-101. It is used for overlaying the inside of vessels to provide the corrosion resistance of stainless steel while utilizing the strength and economy of the low-alloy steels for the wall thickness. A strip electrode feeder is required and special flux is normally used. When the width of the strip is over 2 in. (50 mm), a magnetic arc oscillating device is employed to provide for even burn-off of the strip and uniform penetration.

Another way of increasing the deposition rate of submerged arc welding is to add iron base ingredients to the joint under the flux. This is sometimes called "bulk" welding. The iron in this material will melt in the heat of the arc and will become part of the deposited weld metal. This greatly increases deposition rates without decreasing weld metal properties. Metal additives can also be used for special surfacing applications. This variation can be used with single-wire or multiwire installations. Figure 6-102 shows the increased deposition rates attainable.

Another variation is the use of an electrically "cold" filler wire fed into the arc area. The cold filler rod can be solid or flux cored to add special alloys to the weld metal. By regulating the addition of the proper material, the properties of the deposited weld metal can be improved. It is possible to utilize a flux-cored elec-

FIGURE 6-102 Welding with iron powder additives.



trode for one of the multiple electrodes to introduce special alloys into the weld metal deposit. Each of these variations requires special engineering to ensure that the proper material is added to provide the desired deposit properties.

Industrial Use and Typical Applications

The submerged arc welding process is widely used in the manufacture of most heavy steel products. These include pressure vessels, boilers, tanks, nuclear reactors, chemical vessels, and so on. Another use is in the fabrication of ...ses and beams. It is used for welding flanges to the web (Figure 6-103). The heavy equipment industry is a major user of submerged arc welding. An unusual application is the simultaneous welding of two joints on a triangular-shaped boom of an excavator (Figure 6-104).

FIGURE 6-103 Welding a bridge girder.

FIGURE 6-104 Welding triangular excavator boom—two heads

FIGURE 6-105 Welding track roller forgings.

Another application is the welding together of forged halves to make tractor rollers (Figure 6-105). Shipbuilding is another major user of submerged arc welding, using both machine and automatic methods. Fully automatic submerged arc machines splice plates together and weld stiffeners to plates. Much of the machine welding is done using welding heads mounted on small carriages (Figure 6-106). The overlay of surfaces for corrosion resistance and for wear resistance is also a major use for submerged arc welding.

FIGURE 6-106 Using welding head on carriage in shipyard.

6-7 ELECTROSLAG WELDING

The electroslag welding (ESW) process is a welding process that produces coalescence of metals with molten slag that melts the filler metal and the surfaces of the workpieces. The weld pool is shielded by this slag, which moves along the full cross section of the joint as welding progresses. The process is initiated by an arc that heats the slag. The arc is then extinguished by the conductive slag, which is kept molten by its resistance to electric current passing between the electrode and the workpiece. The consumable guide electroslag welding variation is a method of electroslag welding in which filler metal is supplied by an electrode and its guiding member. Figure 6-107 shows the welder's view of the consumable guide variation.

FIGURE 6-107 Welder's view of consumable guide electroslag welding.

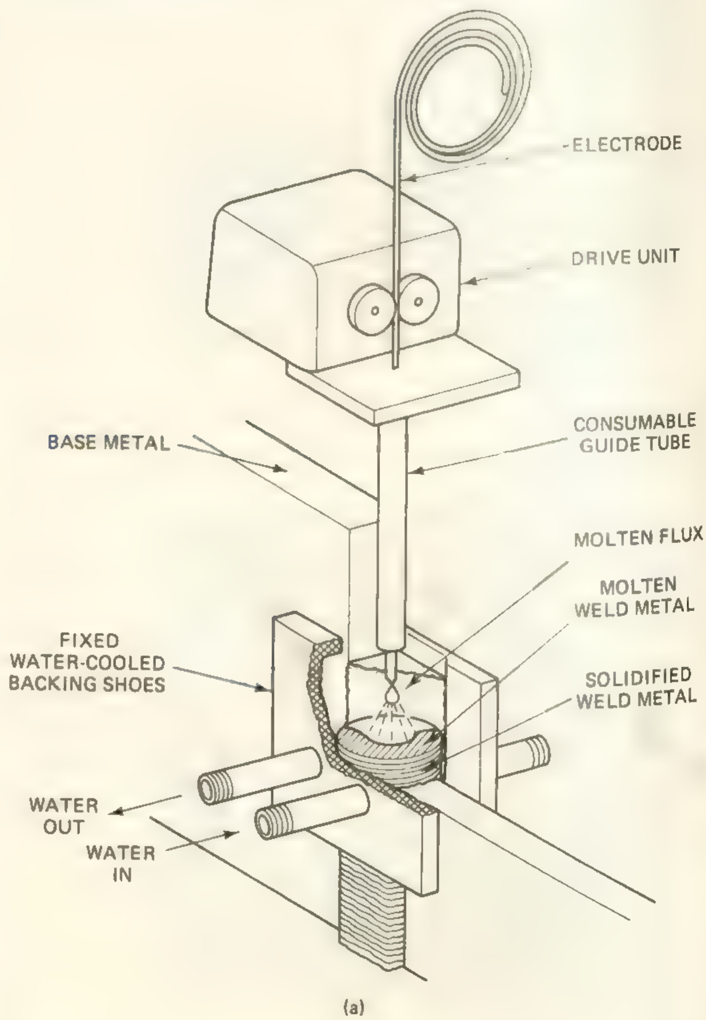
Principles of Operation

Electroslag welding is not an arc welding process. It is included here since it utilizes the same basic equipment as the other consumable electrode welding processes described in this chapter.[23]

The electroslag welding process consumable guide variation is shown in Figure 6-108a. Electroslag welding is done in the vertical position using molding shoes, usually water cooled, in contact with the joint to contain the molten flux and weld metal. The electrode is fed through a guide tube to the bottom of the joint. The guide tube carries the welding current and transmits it to the electrode. The guide tube is normally a heavy wall tube. At the start of the weld, granulated flux is placed in the bottom of the cavity. The electrode is fed to the bottom of the joint and for a brief period will create an arc. In a very short time the granulated flux will melt from the heat of the arc and produce a pool of molten flux. The flux is electrically conductive and the welding current will pass from the electrode through the molten flux to the base metal. The passage of current through the conductive flux causes it to become very hot and it reaches a temperature in excess of the melting temperature of the base metal. The high-temperature flux causes melting of the edges of the joint as well as melting of the electrode and the end of the guide tube. The melted base metal, electrode, and guide tube are heavier than the flux and collect at the bottom of the cavity to form the molten weld metal. As the molten weld metal slowly solidifies from the bottom, it joins the parts to be welded. Shielding of the molten metal from atmospheric contamination is provided by the pool of molten flux. Surface contour of the weld is determined by the contour of the backing shoes. The consumable guide variation of electroslag welding normally uses fixed backing shoes. The welding head does not move vertically and is normally mounted on the work at the top of the weld joint. Multiple electrodes and guides may be employed for welds of larger cross section. It is also possible to oscillate the electrode and guide tube across the width of the joint.

The surface of the solidified weld metal is covered with an easily removed thin layer of slag. The slag loss

FIGURE 6-108a Process diagram (ESW) consumable guide.



must be compensated for by adding flux during the welding operation. A starting tab is necessary to build up the proper depth of the flux so that the molten pool is formed at the bottom of the joint. Run-off tabs are required at the top of the joint so that the molten flux will rise above the top of the joint. Both starting and run-off tabs are removed from the ends of the joint after the weld is completed.

The electroslag welding process, when not using the consumable guide, utilizes a welding head which moves up the joint as the weld is made. Backing shoes move along the joint and rise with the head. Single- or multiple-electrode systems can be employed and they may be oscillated across the width of the joint. All the other factors involved in operating the process are the same except that the guide tube is not used, and therefore the deposit weld metal is supplied entirely by the electrode. See Figure 6-108b for the moving-head version.

Advantages and Major Uses

The **electroslag welding process** is one of the most productive welding processes. Some of its advantages are:

1. *Extremely high metal deposition rates.* Electroslag has a deposition rate of 35 to 45 lbs/hr per electrode.
2. *Ability to weld thick materials in one pass.* There is only one setup and no interpass cleaning since there is only one pass.
3. *High-quality weld deposit.* Weld metal stays molten longer allowing gases to escape.
4. *Minimized joint preparation and fitup requirements.* Mill edges and square flame-cut edges are normally employed.
5. *Mechanized process.* Once started, the process continues to completion. There is little operator fatigue since manipulative skill is not involved.
6. *Minimized materials handling.* The equipment may be moved to the work rather than the work moved to the equipment.
7. *High filler metal utilization.* All the welding electrode is melted into the joint. In addition, the amount of flux consumed is small.
8. *Minimum distortion.* There is no angular distortion in the horizontal plane. There is minimum distortion (shrinkage) in the vertical plane.
9. *Minimal time.* It is the fastest welding process for large, thick material.

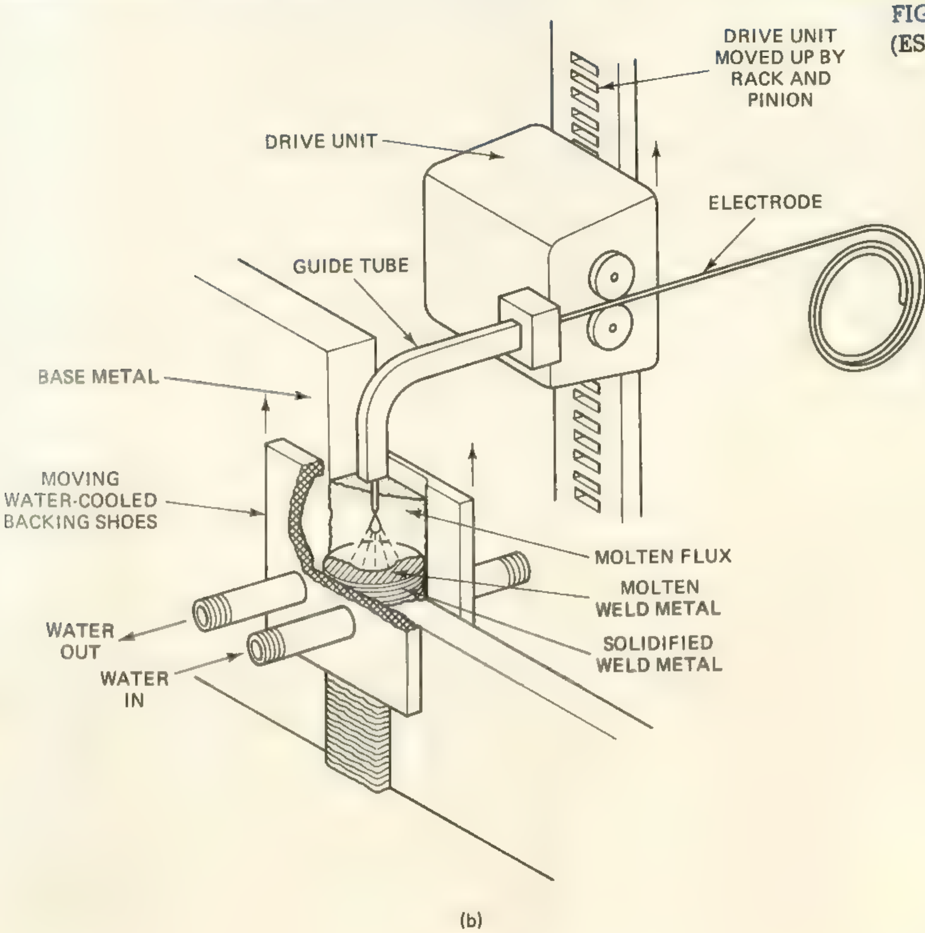


FIGURE 6-108b Process diagram (ESW) head moving.

10. *No weld spatter and minimal metal finishing* of the weld.
11. *No arc flash.* A welding helmet is not required. Tinted safety glasses are required.

Methods of Application and Position Capabilities

The consumable guide version of electroslag welding is applied as a machine operation. Once the process is started it should be continued until the weld joint is completed. The apparatus should be monitored by the welding operator, although little is done in guiding or directing it. Flux is added periodically and the welding operator must monitor the depth of the molten flux pool. When oscillation is used or when moving shoes are used, closer attention is required.

The electroslag welding process is a limited position process. It can be used only when the axis of the weld joint is vertical or varies from the vertical by not over 15°.

Weldable Metals and Thickness Range

The metals welded by the consumable guide electroslag process are low-carbon steels, low-alloy high-strength steels, medium-carbon steels, and certain stainless steels. Quenched and tempered steels can be electroslag welded; however, a post heat treatment may be necessary to compensate for the softened heat-affected zone.

Under normal conditions the minimum thickness metal welded with the consumable guide method is ¾ in. (20 mm). Maximum thickness that has been successfully welded with electroslag is 36 in. (950 mm). To weld this thickness, six individual guide tubes and electrodes were used.

A single electrode is used on materials ranging from 1 to 3 in. (25 to 75 mm) thick. From 2 to 5 in. (50 to 125 mm) thick, the electrode and guide tube are oscillated in the joint. From 5 to 12 in. (125 to 320 mm) thick, two electrodes and guide tubes are used and are oscillated in the joint. If oscillation is not employed, additional guide tubes and electrodes are required. This necessitates additional power sources and wire feed systems, and, therefore, oscillation is preferred where it can be used.

The height of the joint has a definite relationship and must be considered. The process can be used for joints as short as 4 in. (100 mm) and as long or high as 20 ft (6.5 m). It is difficult to oscillate extremely long guide tubes since they become heated and flexible. When two guide tubes are used and properly secured together it is possible for oscillation; however, as the number of tubes increases, the height of the joint must be decreased. The relationship of joint thickness and joint length or height is shown in Figure 6-109.

Joint Design

In electroslag welding, there is just one basic type of weld, the square groove weld (Figure 6-110). The square groove weld can be used to produce butt joints, tee joints, and

FIGURE 6-109 **Base metal thickness and height that can be welded.**

Plate Thickness in.	Plate Thickness mm	Root Opening in.	Root Opening mm	Joint Height ft.	Joint Height meters	Number of Electrodes	Oscillation	Welding Voltage Elec Pos	Total Current Amp DC	Vert. Speed ipm	Vert. Speed mm/min
3/4	19.0	1	25.4	20	6	1	No	35	500	1.40	36.0
1	25.4	1	25.4	20	6	1	No	38	600	1.20	30.0
2	50.8	1	25.4	20	6	1	No	39	700	1.00	25.0
3	76.2	1	25.4	20	6	1	No	52	700	0.80	20.3
2	50.8	1-1/4	31.8	5	1.5	1	Yes	39	700	0.76	19.3
3	76.2	1-1/4	31.8	5	1.5	1	Yes	40	750	0.64	16.3
4	101.6	1-1/4	31.8	5	1.5	1	Yes	41	750	0.52	13.2
5	127.0	1-1/4	31.8	5	1.5	1	Yes	46	750	0.40	10.2
3	76.2	1	25.4	20	6	2	No	40	850	0.50	12.7
4	101.6	1	25.4	20	6	2	No	41	850	0.44	11.2
5	127.0	1	25.4	20	6	2	No	46	850	0.38	9.7
5	127.0	1-1/4	31.8	10	3	2	Yes	41	1500	0.80	20.3
6	127.0	1-1/4	31.8	10	3	2	Yes	42	1500	0.72	18.2
8	203.2	1-1/4	31.8	10	3	2	Yes	45	1500	0.54	13.7
10	254.0	1-1/4	31.8	10	3	2	Yes	48	1500	0.47	11.9
12	304.8	1-1/4	31.8	10	3	2	Yes	51	1500	0.36	9.1
12-18	304.8-457.2	1-1/2	38.1	6	1.8	3	Yes	55	1800	0.18	4.6
18-24	457.2-609.6	1-1/2	38.1	5	1.5	4	Yes	55	2400	0.18	4.6
24-30	609.6-762.0	1-1/2	38.1	4	1.2	5	Yes	55	3000	0.18	4.6
30-36	762.0-914.4	1-1/2	38.1	3	1	6	Yes	55	3600	0.18	4.6

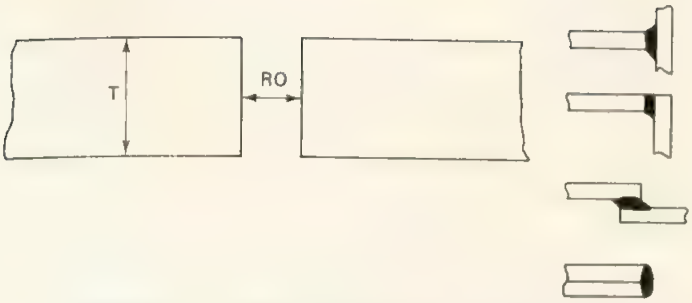


FIGURE 6-110 Electroslag joint designs.

corner joints, and even lap and edge joints. The square groove butt configuration is used for the transition joint, where two thicknesses of plate are joined with a smooth contour from one thickness to the other. The transition can be in the weld metal. Bead or overlay welds can also be made with electroslag. The different weld joints made with the process are shown in Figure 6-111.

In a square groove weld, there are only two dimensions, the thickness of the parts being joined, *T* and the root opening between the parts, *RO*. The root opening can be varied, but it is relative based on the plate thickness. It is desirable to have the root opening as small as possible to use a minimum amount of weld metal. A limiting factor to the minimum root opening is the size of the consumable guide tube and the insulators that are required to keep it from touching the sides of the joint. The guide tube must be of sufficient size to carry the welding current and structurally strong until it is consumed in the flux pool. The root opening must be large enough to provide sufficient volume of the molten flux to ensure stable welding conditions. This becomes one of the limiting factors for making small welds, and is particularly true with the consumable guide variation.

The water-cooled backing shoes are designed to accommodate the different types of joints. Shoes are available for the square groove with minor reinforcing. These are used for butt joints and for other joints where the surfaces of the plates to be joined are flush. For square groove welds involving corner or tee joints, fillet-type shoes are normally used.

Welding Circuit and Current

The welding circuit used for the consumable guide method of electroslag welding is shown in Figure 6-112.

For the consumable guide system, direct-current welding power is normally employed. The electrode is positive (DCEP). The constant-voltage system with the constant-adjustable-speed wire feeder is used.

In the normal electroslag welding process alternating current is often used, especially for three-wire systems. In these cases the constant-feed electrode wire drive motor is used and the characteristics of the power source are close to flat. The electrical characteristics of the conductive molten flux are similar to those of a high-current welding arc.

Welding current per electrode wire may range from as low as 400 A to as high as 800 A. The weld voltage

FIGURE 6-111 Different weld joints made with electroslag welding.

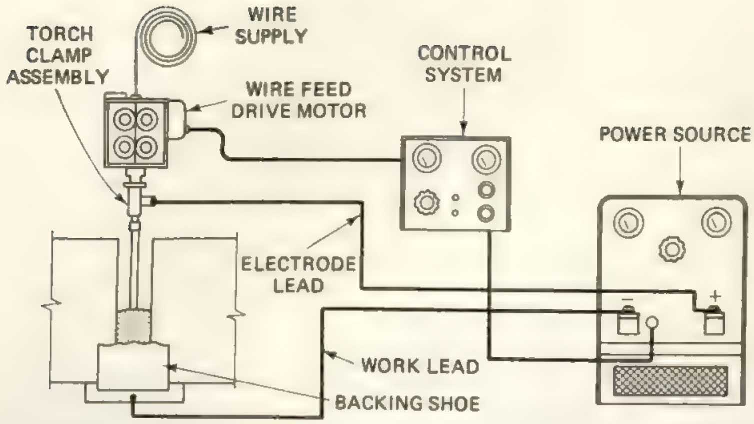


FIGURE 6-112 Circuit diagram (ESW), consumable guide.

will range from 25 to 55 V. The high voltage is extremely important especially when using long guide tubes.

Equipment Required to Operate

The equipment required for the consumable guide electroslag welding process is shown in Figure 6-112. A system can range from one electrode and guide tube assembly up to systems utilizing six electrodes and guide tubes. The systems become more complex as additional electrodes are added. The use of lateral motion or oscillation provides greater latitude of the consumable guide method. All the electrode wires are mounted on one oscillating assembly, so only one oscillating device and control are required.

The power source used for the consumable guide electroslag welding process should be a direct-current welding machine of the constant-voltage (CV) type. It must be rated at a 100% duty cycle since some electroslag welds take hours to complete. The current capacity of the machine must exceed the current required for a single electrode according to the welding procedure schedule. The power source should have high voltage ratings since starting voltages as high as 55 V are sometimes required. Transformer–rectifier machines are best suited for electroslag welding. Primary contactors and provisions for remote control including voltage adjustments should be included.

Normally, the wire feed motor is mounted over the welding joint; however, it can be mounted elsewhere and the electrode wire can be conducted to the joint by flexible conduits. The oscillation system is used for heavier thicknesses. This requires a motor control for oscillating, limit switches for adjusting the width of oscillation, and a control circiut for adjusting the oscillation speed and dwell at each end of oscillation.

When water-cooled backing shoes are used, a system for water circulation and heat removal is required. When running water is available and when it can be easily disposed of, this is the simplest solution. However, water circulating systems, which include heat exchangers, can be used. The size of the heat exchanger must be sufficiently great to remove the heat generated in the weld.

Materials Used

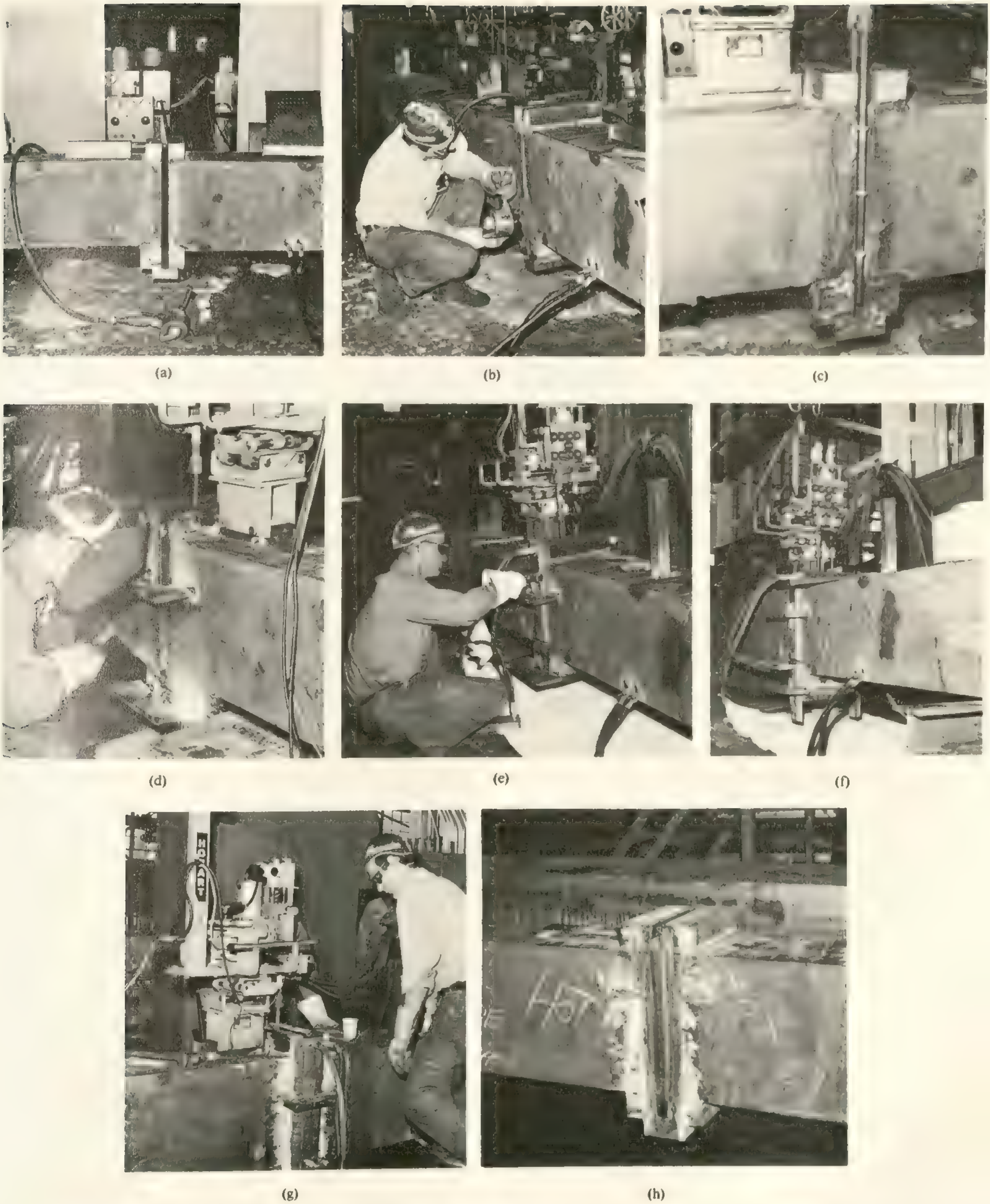
Three materials are routinely used in making consumable guide electroslag welds: the flux, electrode wire, and the guide tube. These are specified by the AWS "Specifications for Consumables Used for Electroslag Welding of Carbon and High Strength Low Allow Steels."[24] There are other materials used, including runoff tabs and the starting sump. These are reusable and must be the same thickness and composition as the base metal. Insulating material is used for certain applications. Insulators are sometimes required around the bare guide tube to avoid short circuiting the system if the guide tube comes in contact with the retaining shoes or the face of the weld joint. Other reusable items are the strong backs used to hold the retaining shoes against the weld joint. Wedges are used to hold the retaining shoes in place. The strong backs and wedges are reused many times. When more than one electrode is used, a steel wool ball is placed at the bottom of the joint under the electrode wire to aid arc initiation. Steel wool also can be used for single wire applications, although it is not normally required.

When the work surface is irregular it is necessary to install a putty-like material to seal the cracks between the shoes and the work. Commercial materials such as furnace sealing compound can be used. Figure 6-113 shows the preparation of the joint, the attachment of the strong backs, the guide tube with insulators, and the installation of the retaining shoes.

Normal functions for an electroslag flux are:

1. Providing heat to melt the electrode and base metal
2. Conducting the welding current
3. Protecting the molten weld metal from the atmosphere
4. Purifying or scavenging the deposited weld metal
5. Providing stable operation

There are two types of granular fluxes normally



(a) (b) (c)

(d) (e) (f)

(g) (h)

FIGURE 6-113 Sequence of preparing and making an electroslag weld.

used for electroslag with the consumable guide tube. One is a starting flux and the other is a running flux. The starting flux is designed to bring the electroslag process into quick stabilization. It melts quickly and wets the bottom of the sump to facilitate starting. The running flux is designed to provide the proper balance for correct electrical conductivity, correct bath temperature and viscosity, and the proper chemical analysis. Running flux will operate over a wide range of conditions. Only a relatively small amount of electroslag flux is used; approximately ¼ lb (100 g) of flux is used per vertical foot (320 mm) of the joint or height.

The *electrode* for consumable guide electroslag welding supplies over 80% of the deposited weld metal. The guide tube supplies the remainder. The electrode wire must match the base metal. Since an electroslag weld deposit is similar to a casting, it is essential that the properties of this *as-cast* metal should overmatch the mechanical properties of the parts being joined. It is important to consider the dilution factor provided by the base metal. In a consumable guide weld the dilution runs from a low of 25% to a high of 50% base metal. The amount of dilution of base metal depends on the welding conditions.

The flux adds no alloys and has little effect on the weld deposit in relationship to the analysis of the wire. In general, electrode wires designed for gas metal arc welding and submerged arc welding are employed for electroslag welding. The 3/32-in. (2.4-mm) electrode size is the most common. It is the most easily used to feed through a guide tube and produces the highest deposition rate.

The *consumable guide tube* melts just above the surface of the molten slag bath. A guide tube must be used whenever the length of the weld is 6 in. (160 mm) or over, assuming that the head is stationary.

When a bare guide tube is used and if the weld is over 12 in. long (304 mm), insulators should be placed on the tube to avoid the guide tube coming in contact with the sidewall or face of the joint or the retaining shoes.

Coated guide tubes are also available and the coating is an effective insulator particularly when working in tight joints.

There are several variations of the consumable guide tube system. In some cases bars are tack-welded to the guide tube or tubes are tacked on edges of bars. These bars contribute metal to the weld deposit.

Deposition Rates and Quality of Welds

Deposition rates of the electroslag welding process are among the highest. Figure 6-114 shows the deposition rate versus welding current of the 3/32-in. (2.4-mm) electrode wire and of the ⅛-in. (3.2-mm) electrode wire.

The electroslag welding process produces a high-quality weld metal deposit. The high quality of electroslag

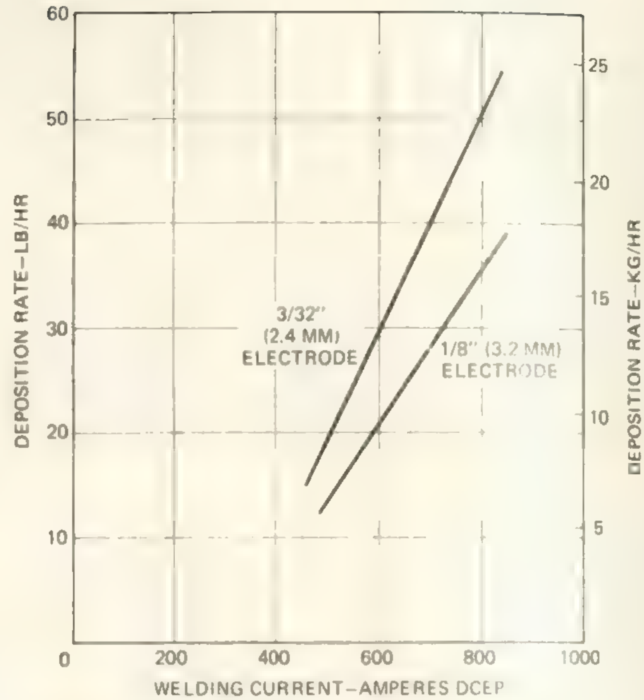


FIGURE 6-114 Deposition rate (ESW).

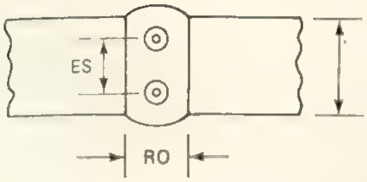
weld metal is the result of progressive solidification, which begins at the bottom of the joint or cavity. There is always molten metal above the solidifying weld metal, and the impurities, which are lighter, rise above the deposited metal and collect only at the very top of the weld in the area that is normally discarded.

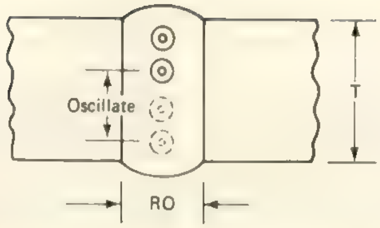
Electroslag welding is a low-hydrogen welding process, since hydrogen is not present in any of the materials involved in making the weld. Because of the slow cooling rate, any impurities that are in the base metal and are melted during the welding process have time to excape. The cooling rate of the electroslag weld is much slower than the cooling rate of welds made by other arc welding processes. The slow cooling rate allows large grain growth in the weld metal and also in the heat-affected zone of the base metal. The slow cooling rate minimizes the risk of cracking and reduces the hardness in the heat-affected zone sometimes found in conventional arc welds.

Weld metal produced by electroslag welding will qualify under the most strict codes and specifications. The ductility of the weld metal is relatively high, in the range 25 to 30%. The impact requirements for electroslag welds will meet those required by the AWS structural welding code. V-notch Charpy impact specimens producing 5 to 30 ft-lb at 0°F are normal and expected.

Weld Schedules

Welding procedure schedules for electroslag welding with the consumable guide method are shown in Figure 6-115.





Two Electrodes -Non oscillating

Thickness T in.	mm	Maximum Height H ft.	Meters	Root RO Opening in.	mm	Electrode Spacing ES in.	mm	Welding Volts EP	Current Amperes DC
3	75	20	6	1	25	2-1/2	62	41	850
4	100	20	6	1	25	2-1/2	62	44	850
5	125	20	6	1	25	2-1/2	62	47	850

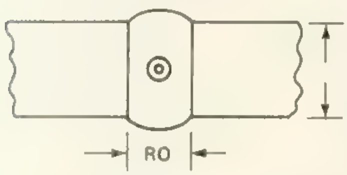
Guide tube size–5/8" (15.9 mm) O.D. x 1/8" (3.2 mm) I.D.

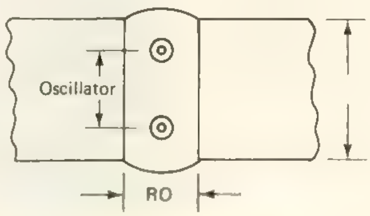
Two Electrodes–with Oscillation

Thickness in.	mm	Maximum Height H ft.	Meters	Root RO Opening in.	mm	Oscill. Length in.	mm	Traverse Speed (2) ipm	mm	Welding Volts EP	Current Amperes DC
[illegible]	125	10	3	1-1/4	31.4	1	25	20	500	42	1500
[illegible]	150	10	3	1-1/4	31.4	2	50	40	1000	43	1500
[illegible]	200	10	3	1-1/4	31.4	4	100	80	2000	46	1500
[illegible]	250	10	3	1-1/4	31.4	6	150	120	3000	49	1500
[illegible]	300	10	3	1-1/4	31.4	8	200	120	3000	52	1500

(a)

Guide tube size–5/8" (15.9 mm) O.D. x 1/8" (3.2 mm) I.D.
(1) Electrode diameter 3/32".
(2) Based on 10 second oscillation cycle.
(3) Water cooled shoes and Porta-slag flux used.





Single electrode–Non oscillating

Thickness T in.	mm	Maximum Height H ft.	Meters	Root RO Opening in.	mm	Welding Volts EP	Current Amperes DC
3/4	19	20	6	1	25	36	500
1	25	20	6	1	25	39	600
2	50	20	6	1	25	40	700
3	75	20	6	1	25	53	700

(b)

Guide tube size–1/2" (12.7 mm) O.D. x 1/8" (3.2 mm) I.D.

Single electrode–with Oscillation

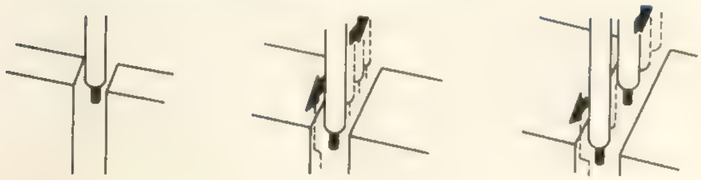
Thickness T in.	mm	Maximum Height H ft.	meters	Root RO Opening in.	mm	Oscill. Length in.	mm	Traverse Speed (2) ipm	mm	Welding Volts EP	Current Amperes DC
2	50	5	1.5	1-1/4	31.4	1-1/4	31.4	25	625	40	700
3	75	5	1.5	1-1/4	31.4	1-1/4	31.4	45	1125	41	750
4	100	5	1.5	1-1/4	31.4	1-1/4	31.4	65	1625	44	750
5	125	5	1.5	1-1/4	31.4	1-1/4	31.4	85	1925	47	750

Guide tube size–5/8" (15.9 mm) O.D. x 1/8" (3.2 mm) I.D.
(1) Electrode dia. 3/32"
(2) Based on 10 second oscillation cycle
(3) Water cooled shoes and Porta-slag flux used.

FIGURE 6-115 Welding procedure schedule (ESW).

Welding procedure schedules are based on welding low-carbon steel under normal conditions using water-cooled copper shoes, and the ⅝-in. (16-mm)-outside-diameter guide tube with a ⅛ in. (3.2 mm) inside diameter unless otherwise specified. The electrode diameter is $\frac{3}{32}$ in. (2.4 mm) and proprietary starting and running fluxes are used. Oscillation speed is based on the number of seconds per cycle, which is shown as a rate of speed. There is a dwell time at each end of oscillation, which is normally 4 seconds. Electrode oscillation is shown in Figure 6-116.

FIGURE 6-116 Electrode oscillation.



Welding Variables

Electroslag welding differs from arc welding processes in that the base metal melting results from localized heat generated in the molten slag pool instead of from an arc. The heating involved in electroslag welding is concentrated in a volume of molten flux which is the product of the metal thickness by the root opening by the slag pool depth.

In the arc welding processes, the localized heating is confined to the much smaller area of an arc and puddle, but the arc is at a much higher temperature. The operation of electroslag welding is thus different from the familiar arc processes.

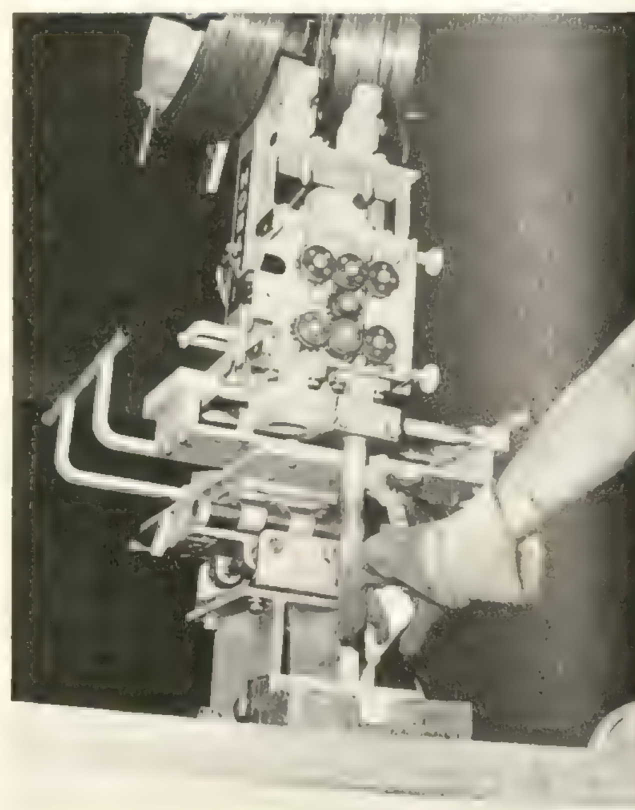
In electroslag welding the metal surface to be melted (joint side walls) is parallel to the axis of the electrode. Thus increasing welding current does not increase the depth of penetration of the sidewalls of the base metal. The higher the welding current, the higher the deposition rate.

With all arc welding processes, an increase in arc voltage causes the weld bead to widen. In electroslag welding, the same thing is true, but now this widening causes an increase in the depth of penetration into the sidewall. The increased voltage raises the slag bath temperature and causes more of the base metal or sidewall to melt. Increase voltage to increase depth of fusion. Excessively high voltage will cause undercutting. Too low a voltage may result in arcing between electrode wire and the molten weld metal at the bottom of the flux pool. The operator must be continually alert to make various adjustments as required during the welding operation. The operator must have a good operating knowledge of electroslag welding because of the different effects of changing the various parameters.

The depth of the molten slag pool should be checked if possible. When the pool is accessible to the operator a dipstick can be used to determine its depth. Experience will quickly show that when the pool is quiet and the process is running without sparking or sputtering that the pool depth is correct. If the pool depth becomes too shallow, sparks will emit from the surface and can be seen by the operator. Additional flux should be added to the pool. This is simply done with a container, which is shown in Figure 6-117.

If the backing shoes leak and water gets into the weld cavity, the operation must be stopped. This can create a safety hazard and will create gross porosity in the weld metal. With respect to water-cooled shoes, the operator must ensure that the water flow is uninterrupted during the entire welding operation.

FIGURE 6-117 Operator adding flux during welding.



Safety Considerations

The major safety factor is the presence of a large mass of molten slag and molten weld metal. The high welding current creates a large mass of metal which must be contained within the weld cavity. If the backing shoes should

fail and allow the molten metal to escape, it is best to evacuate the area, turn off the equipment, and wait for the metal to solidify. Obviously, the surface under the welding operation should be noncombustible. The work being welded must be securely braced to eliminate the possibility of it falling.

Limitations of the Process

The major limitation is the welding position limitation. It can be used only when the axis of the weld is vertical. A tilt of up to 15° is permitted, but beyond this the process may not function correctly. The second limitation is that the process can be used only on steels.

Variations of Process

Electroslag Cladding This is a variation that deposits surfacing materials on base metals. It is very similar to strip cladding with the submerged arc welding process except that the heat required to melt the surface of the base metal, the strip, and the flux is generated by resistance heating from the current flow to the strip and through a shallow layer of electroconductive slag (Figure 6-118). Electroslag cladding has become popular because it provides for high deposition rates and low dilution. In addition, it can be used with the same equipment as that used for submerged arc strip cladding. Magnetic oscillation of the arc is recommended for best results. The electroslag process will deposit approximately two times as much metal per hour as the submerged arc method. Dilution is controllable and is usually less than with submerged arc. It will range from 10 to 20%. It is possible to clad ferritic, martensitic, and austenitic stainless steels, nickel-base alloys, and some hard-surfacing materials. Strip width is approximately 2 in. (50 mm) to 2½ in. (60 mm). The major use for electroslag cladding is the deposition of austenitic stainless steel on carbon steel for tube sheets and/or other corrosive applications.

Industrial Use and Typical Applications

The major user of electroslag welding has been the heavy plate fabrication industry, which includes manufacturers of frames, bases, metalworking machinery, and so on. A frequent use of the process is the splicing of rolled steel plates to obtain a larger piece for a specific application. A typical application is the splicing of an 8-in. (203-mm)-thick plate, 12 ft (4 m) wide, to make a press frame (Figure 6-119). The weld joint was set up in the vertical position, strong backs were attached, and the two-wire feeder was placed at the top of the joint. Four water-cooled backing shoes were used, two on either side, which

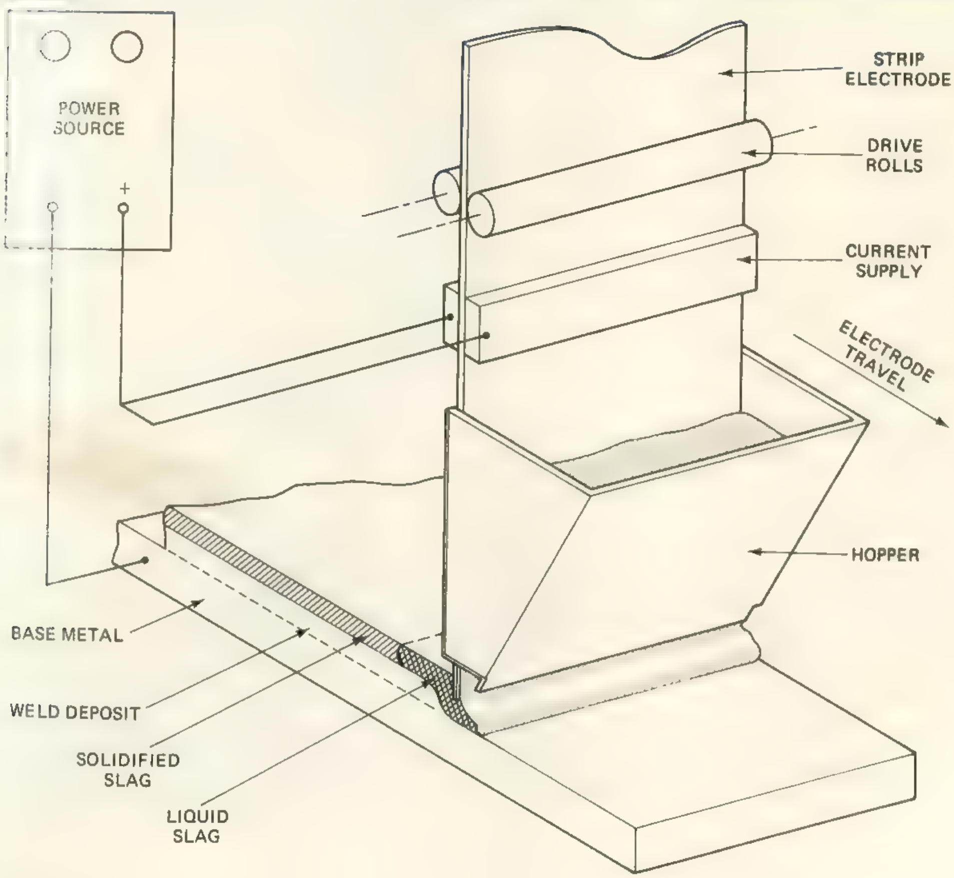


FIGURE 6-118 Electroslag cladding.

FIGURE 6-119 Splicing 8-in.-thick 12-ft-wide plates.

were moved progressively from bottom to top until the weld was completed. Previously, with submerged arc welding and turning the plate over after every few passes, the splicing operation required 80 hours. With the consumable guide electroslag process the weld was completed in slightly over 4 hours.

Another machinery application is shown in Figure 6-120. This is the end frame for a steel mill roll. Five electrode wires are being used to make this massive weld. The top side will be positioned and then welded the same way.

Another user of electroslag is the structural steel industry, for making subassemblies for steel buildings. It has also been used for field erection on the building site. A common application is the welding of continuity plates inside box columns. The continuity plate carries the load from one side of the column to the other side at the point of beam-to-column connections. Continuity plates must be welded with complete penetration welds to the two sides of the box column. Figure 6-121 shows an automatic fixture, which provides for two welding operations simultaneously.

The electrical machinery industry also utilizes electroslag welding. Electric motor housings are rolled from a single plate, and a single weld is made to join the two abutting edges. In other cases the material is heavier or

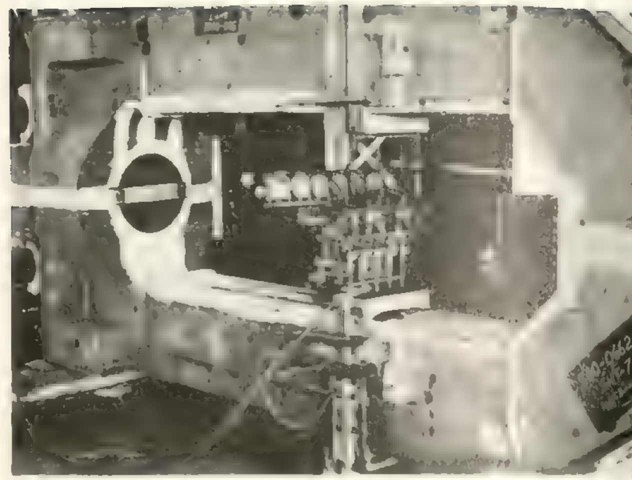
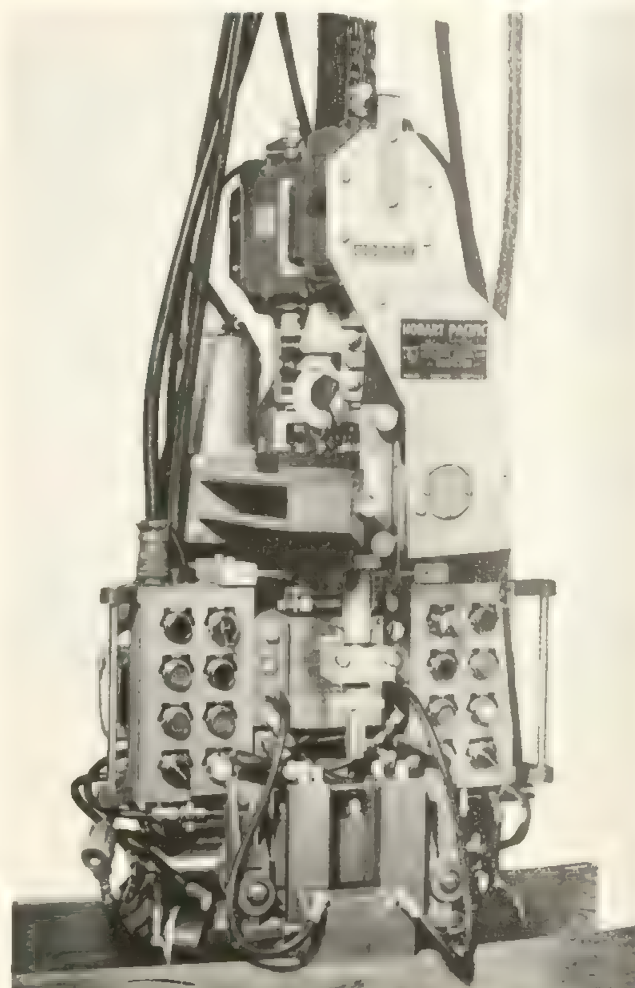


FIGURE 6-120 Large end frame for steel mill rolls electroslag welded.

FIGURE 6-121 Automatic machine for box column continuity plate.



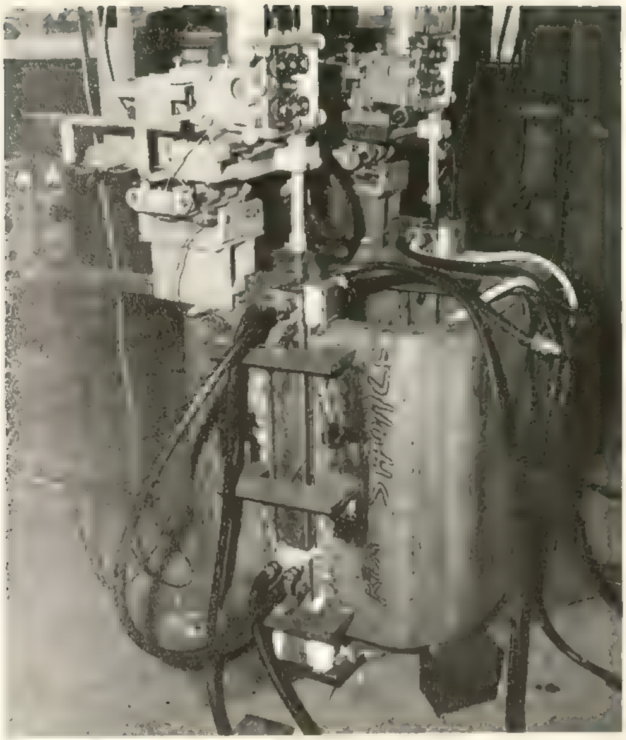


FIGURE 6-122 **Motor housing: two welds made simultaneously.**

the housing might be square. Figure 6-122 shows two sides of a motor housing being welded simultaneously. Electroslag reduces total cycle time because the housing was previously welded with submerged arc one joint at a time.

There are many, many other applications of the consumable guide version, both in the shop and in the field. It is expected that electroslag welding will find more applications as its productivity is better known by more users.

6-8 ELECTROGAS WELDING

The electrogas welding (EGW) process is "an arc welding process that uses an arc between a continuous filler metal electrode and the weld pool, employing vertical position welding with backing to confine the molten weld metal. The process is used with or without an externally supplied shielding gas and without the application of pressure." The electrodes may be either flux cored or solid. Shielding may or may not be obtained from an externally supplied gas or gas mixture. There are two basic variations. One uses the solid consumable electrode wire and externally supplied shielding gas normally CO_2; the second utilizes the flux-cored electrode wire and does not normally use an external shielding gas since shielding gases are produced by the flux-cored electrode as it is consumed in the arc.

Principles of Operation

The electrogas process is the solid electrode wire and externally supplied shielding gas variation (Figure 6-123). This process utilizes the heat of an arc between a continuously fed consumable electrode wire and the weld pool. The heat of the arc melts the surfaces of the base metal and the end of the electrode. The metal melted from the electrode as well as metal melted on the surface of the abutting base metal of the weld joint collect at the bottom of the cavity formed between the parts to be welded and the backing shoes. This is molten weld metal which solidifies from the bottom of the joint and joins the parts to be welded. Shielding of the molten metal from the atmosphere is provided by shielding gas, which flows into the cavity and excludes atmospheric air. Electrogas welding is similar to electroslag welding except that no molten slag is employed and the arc is continuous from start to finish.

The similarities are that electrogas welding is done in the vertical position, usually using backing shoes which may or may not be water cooled. The backing shoes are in contact with the joint to contain the molten weld metal in the cavity. The electrode is fed to the bottom of the joint by means of a wire feeding system and contact tip. This mechanism will travel vertically along the joint to maintain the normal arc length between the tip of the electrode and the molten weld metal. In many cases one backing shoe is stationary and can be made of steel, thus becoming part of the joint, or made of copper, so that it does not become part of the weld joint. On the side with the wire feed mechanism a moving shoe is normally employed which rises with the wire feed mechanism to maintain the weld metal within the cavity. Normally, only one electrode wire is used for making a weld.

A starting tab is necessary at the start of the weld since it takes a few moments for the process to stabilize and produce high-quality weld metal. Run-off tabs are normally required at the top of the joint so that the weld metal of the joint will extend above the parts being joined. Both the starting and run-off tabs are removed from the ends of the joint after the weld is completed.

Methods of Application and Position Capabilities

The electrogas welding process is continuous. Once the process has started, it should be continued until the weld joint is completed. The welding operation should be monitored by the operator. The principal purpose is to provide guidance or ensure that the electrode and arc is centered in the joint. It is important to maintain shielding

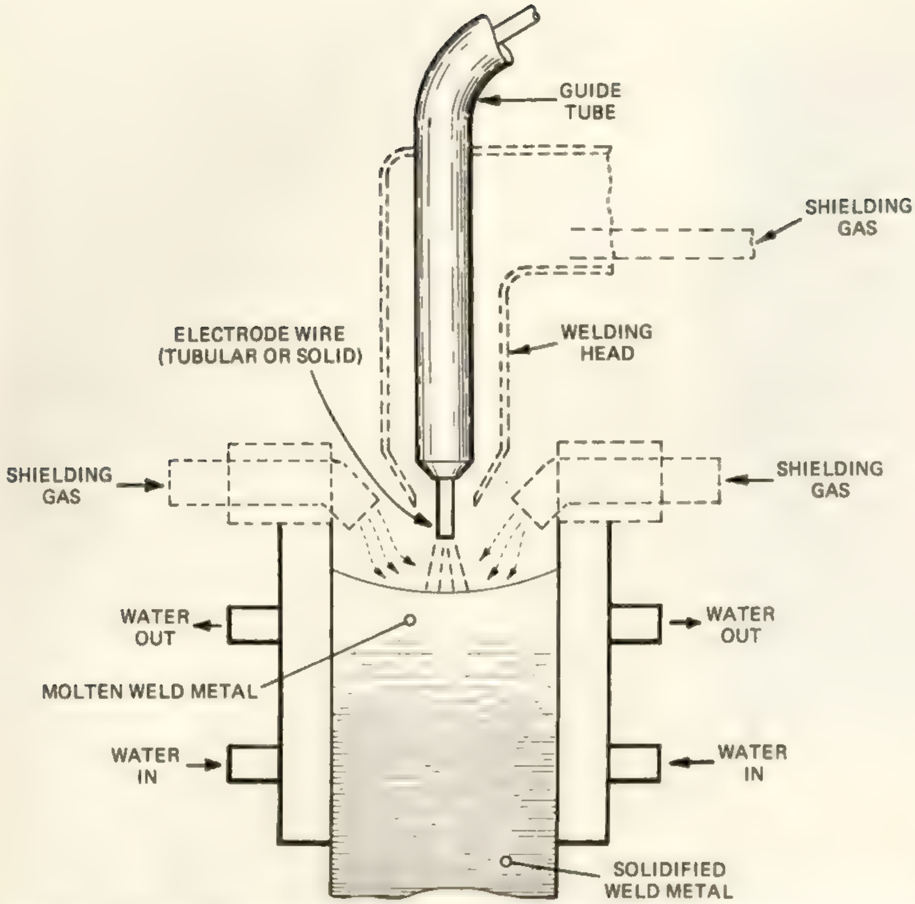


FIGURE 6-123 Process diagram (EGW).

gas flow during the entire welding operation. The arc voltage is utilized to provide control of the vertical motion of the apparatus. The motion is controlled so that the arc length will remain constant from start to finish.

The electrogas welding process is a limited position process. It can be used only when the axis of the weld joint is vertical or varies from the vertical by not over 15°.

Weldable Metals and Thickness Range

The metals welded by the electrogas process are low-carbon steels, low-alloy high-strength steels, medium-carbon steels, and certain stainless steels. The process can also be used for welding quenched and tempered steels providing that the correct heat input is maintained for the type of steel being welded.

Under normal conditions the minimum thickness of metal welded with electrogas is ⅜ in. (10 mm). The maximum thickness utilizing one electrode is ¾ in. (20 mm). This can be increased by oscillating the electrode.

The height (or length) of the joint is practically unlimited. The process can be used for joints as short as 4 in. (100 mm) and/or as long or high as 50 ft (18 m). The only limitation is the length of the elevating mechanism for moving the weld head vertically.

Joint Design

Fillet welds and groove welds can be produced by the electrogas process. For making fillet welds a single backing shoe is required. This shoe fits on the face of the fillet and provides the fillet size. For groove welds, the square groove design can be used up to the maximum possible with one electrode (usually ¾ in.). The V-groove design can also be used up to the maximum thickness or size of the V groove. If thicker metals need to be welded, the double-V-groove design can be used. This offers the opportunity of making each half of the double V groove independently. When this is done, the backing shoes must be designed specifically for the joint detail. The backing shoe for the root or the narrow portion of the V would fit in from the back side. The backing shoe for the face of the weld would be the same as for the square groove weld. When making the second weld of the double V joint, the back side backing shoe would not be required since the initial weld performs this function.

The ability to make fillets and V-groove welds is one of the advantages of the electrogas welding process. The joint design for electrogas welding can be the same as for shielded metal arc welding, gas metal arc, or flux-cored arc welding. The backing shoes, particularly for the face of welds, should have sufficient relief to provide the normal reinforcement of a groove weld. For fillet

welds a smooth contour of the fillet can be obtained with the correct cross section of the backing shoe.

Welding Circuit and Current

The welding circuit used for the electrogas welding process is essentially the same as for the other continuous or consumable electrode processes. The block diagram for electrogas welding is shown in Figure 6-124. Direct-current welding power is normally employed and the electrode is positive (DCEP). The constant-voltage system with the constant/adjustable-speed wire feeder is used. The welding current may range from as low as 100 A to as high as 400 A. The welding voltage will range from 20 to 30 V. The welding voltage is used to control the vertical travel speed of the welding head. The welding head apparatus normally includes the moving shoe required on the electrode side of the weld joint.

Equipment Required to Operate

The equipment required for the electrogas welding process is shown in Figure 6-124. The system normally utilizes one electrode. Oscillation of the electrode within the weld joint is not normally used. The welding head assembly is normally mounted on a carriage, which is elevated as the weld progresses. For shipbuilding, the entire apparatus, which may also carry the welding operator, will move from the bottom of the side of the ship to the top. This is done with a precision elevating system controlled by the welding arc voltage. Smaller but similar equipment is utilized for welding large storage tanks. The control for the entire operation is mounted with the welding head and available to the welding operator. This enables the operator to start the weld and have it run continuously until the joint is completed.

The power source used for electrogas welding should be a direct-current machine of the constant-voltage (CV) type. It must be rated at 100% duty cycle since some electrogas welds take over an hour to complete. The capacity of the welding power source must exceed the current required for the single electrode according to the welding procedure schedule. Rectifier machines are best suited for electrogas welding.

The wire drive feed motor and control system is the same as that used for other consumable electrode wire processes. Normally, the wire feed motor is mounted adjacent to the weld joint, with a contact tube delivery

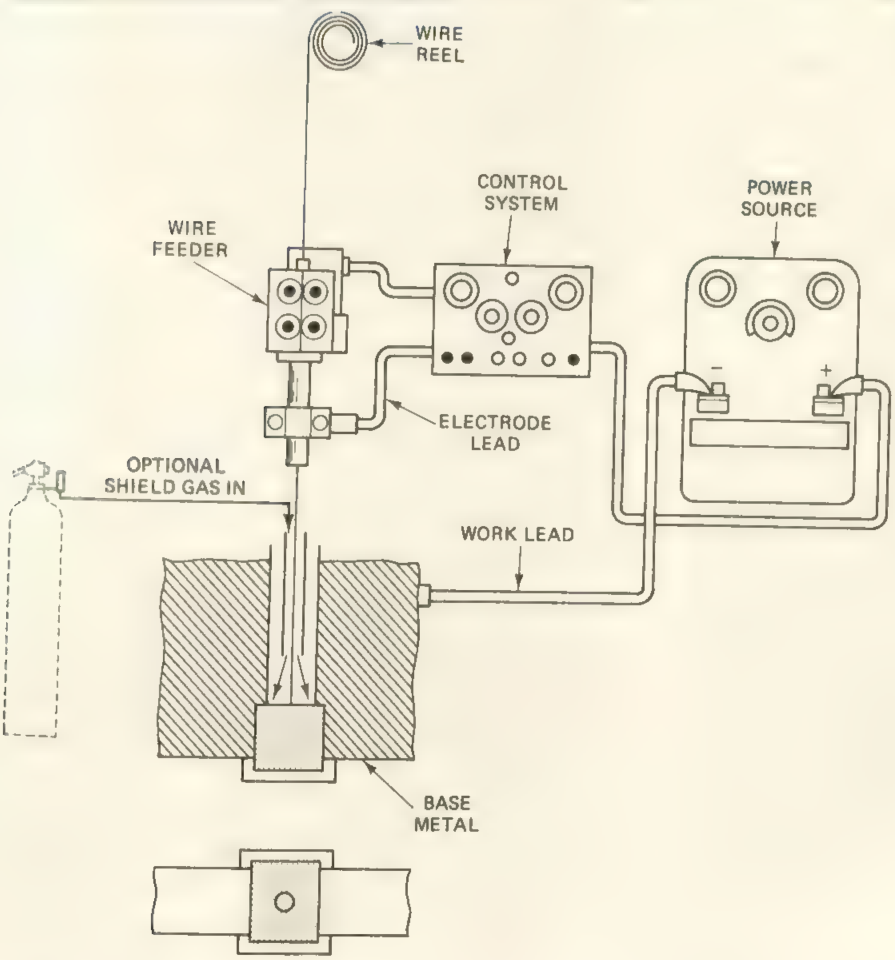


FIGURE 6-124 Circuit diagram (EGW).

system bringing the electrode into the center of the joint and pointed downward within the cavity.

The shielding gas delivery system must provide efficient shielding of the molten metal to avoid atmospheric contamination. The start and stop of shielding gas flow will be controlled by the total system.

The moving backing shoes are normally water cooled and designed for the specific joint and application. They provide a water flow channel and are made of copper to avoid melting. The water circulation should be of such volume as to avoid any surface melting of the shoes. A water circulator that includes a heat exchanger is normally used. The size of the heat exchanger must be sufficiently great to remove the heat generated in the weld. More details concerning electrogas welding is given in the AWS "Recommended Practice for Electrogas Welding."[25]

Electrode Wire

The electrode wire must be matched to the material being welded and can be specified according to the AWS specification "Consumables Used for Electrogas Welding of Carbon Steels and High Strength Low Alloy Steels."[26] This covers the solid wires and the flux-cored wires. The shielding gas, which is normally CO_2, would be specified as welding grade.

Deposition Rates and Quality of Welds

The deposition rate of electrogas welding is relatively high. Flux-cored wire deposition rates vary with wire types and manufacturers since the ratio of fill to metal varies.

Electrogas welding is considered a low-hydrogen type of welding process since hydrogen is not present in any of the materials involved in making a weld. Electrogas welds possess properties and characteristics that surpass welds made with shielded metal arc welding. The higher-than-normal heat input of electrogas weld reduces the cooling rate, which helps reduce impurities. This allows larger grain growth of the weld metal and also in the heat-affected zone of the base metal. This lower cooling rate minimizes the risk of cracking and reduces the high hardness zones in the weld and heat-affected zone sometimes found with shielded metal arc welding. The hardness of the weld is normally uniform across the weld's cross section and is very similar to the unaffected base metal.

Weld metal produced by electrogas welding will qualify under most codes and specifications. The ductility of the weld metal of electrogas weld is relatively high, in the range of 25% elongation. Impact requirements for electrogas welds will meet those required by the AWS Structural Welding Code. V-notch Charpy impact specimens producing 5 to 30 ft-lb at 0 °F (19 to 60 joules at −10 to −34 °C) are normal and expected.

Weld Schedules

Welding procedure schedules for electrogas welding are shown in Figure 6-125. These may not necessarily be the only conditions that can be used. It is possible that welding parameters can be adjusted to obtain optimum results; however, qualification tests should be made before utilizing published welding procedure schedules, especially when welding critical jobs.

Tips for Using the Process

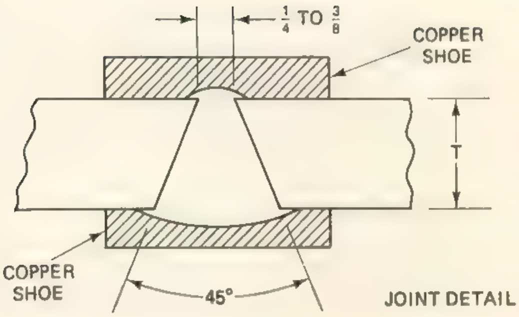
Even though the electrogas process is normally a machine process, the operator must be continually alert and make adjustments required during the welding operation. The operator must have a good operating knowledge of electrogas welding because of the different effect of changing various parameters. In some respects the effects are opposite those expected when using the gas metal arc welding process. For example, increasing the wire feed speed of the electrode feed increases the welding current but does not increase the sidewall penetration of an electrogas weld. Increasing the welding voltage increases the gap between the end of the electrode and the molten metal, and this increases sidewall penetration.

If the electrode wire is not properly centered, the penetration on the opposite sides of the weld joint will be nonuniform. The electrode should be centered between the backing shoes. However, if one shoe is steel rather than copper, the electrode should be directed to the side of the joint with the copper shoe.

If the backing shoe does not fit tightly along the joint, the molten weld metal may run out of the cavity. If this happens, steps must be taken immediately to stop the leak. This is done by using a putty-like sealing preparation made of clay. Any leaks should be immediately sealed off to avoid loss of the weld.

The operator should make a rough calculation to determine the amount of electrode wire required for a specific joint. Sufficient wire should be available on the machine prior to starting the weld. Once the weld is started, it should run continuously until it is finished. If the operation stops for any reason, the machine should immediately be turned off, correction made, and the weld restarted. At the point of stopping and restarting, there is normally an unfused area that must be gouged out and rewelded with an arc welding process capable of welding in the vertical position.

If the backing shoes leak and water gets into the weld cavity, the operation must be stopped. This can create a safety hazard and will create gross porosity of the weld metal. With respect to water-cooled shoes, the



Material Thickness, T		Electrode Size		Electrode Oscillation	Voltage (Electrode Positive)	Current DC	Travel Speed	
in.	mm	in.	mm				in./min	m/hr
$\frac{1}{4}$	6.4	$\frac{1}{8}$	3.2	No	31-33	300-325	8-9	12-14
$\frac{5}{16}$	8	$\frac{1}{8}$	3.2	No	33-35	300-325	7-8	11-12
$\frac{3}{8}$	10	$\frac{1}{8}$	3.2	No	34-36	325-350	6-7	9-11
$\frac{1}{2}$	12.7	$\frac{1}{8}$	3.2	No	34-36	350-400	6-7	9-11
$\frac{3}{4}$	19	$\frac{1}{8}$	3.2	No	42-44	600-650	6-7	9-11
1	25	$\frac{1}{8}$	3.2	0 to $\frac{1}{4}$	44-46	650-700	5-6	7-9
$1\frac{1}{4}$	32	$\frac{1}{8}$	3.2	$\frac{1}{2}$	46-48	650-700	4-5	6-7

FIGURE 6-125 Electrogas welding procedure schedules (EGW).

operator must ensure that water flow is uninterrupted during the entire welding operation.

Safety Considerations

The safety factors involved with electrogas welding are much the same as for the other continuous wire arc welding processes. A welding helmet and shield should be worn because the arc is continuous from start to finish. A safety factor involved is the presence of larger-than-normal amounts of molten weld metal. If this metal escapes, it creates a safety hazard and a fire hazard. The work being welded must be securely braced to eliminate the possibility of it falling. In addition, since vertical heights are involved, the equipment should be safety-related to protect personnel from falling.

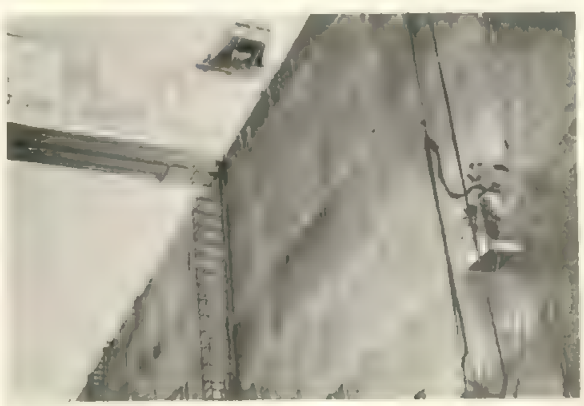
Limitations of the Process

The major limitation is the welding-position limitation. The process should not be used if the joint is at an angle in excess of 15° from vertical. The other limitation is that only steel can be welded.

Industrial Use and Typical Applications

The major use of electrogas welding has been in the field erection of storage tanks for oil, water, and other liquids. Another user is the shipbuilding industry, for joining shell plates (Figure 6-126).

FIGURE 6-126 Electrogas welding used in shipbuilding.



6-9 OTHER CONSUMABLE ELECTRODE WELDING PROCESSES

Automatic welding began in the early 1920s, but the covered electrode which produced higher-quality weld metal replaced bare electrode automatic welding applications. Automatic welding was improved by using lightly coated wires and later by using knurled wires which held more of the stabilizing and deoxidizing coating materials. The quality was not as good as that produced by covered electrodes.

Many efforts were made to produce an all-position automatic welding process that would produce high-quality weld metal. The coating on the *covered wire* created two problems. The coating was fragile and brittle and could not be bent into coils without cracking and falling off. The coatings were insulators and the welding current could not be introduced into the metal core wire in an efficient manner. Several developments deserve brief consideration.

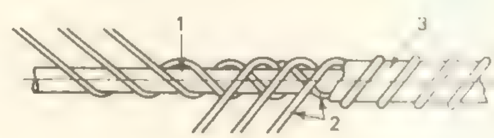
One early attempt was made to extrude coatings on large-diameter electrode wire and then coil the wire into extremely large diameter coils. At the welding head a cutter removed the coating from one small area of the wire. The welding current was conducted to the core wire through the slot in the coating by multiple pickup shoes. This process had limited success.

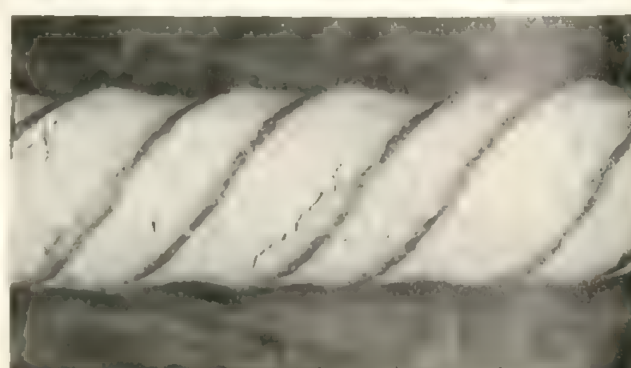
Another variation was known as the *impregnated-tape* metal arc welding process. Shielding is obtained from decomposition of an impregnated tape wrapped around the bare electrode as it fed into the arc. The tape, similar to insect screen wire, were woven in narrow widths, impregnated with stabilizing and deoxidizing materials, and then coiled. This tape was wrapped around the bare electrode wire below the current pickup jaws and above the arc. It provided arc shielding, deoxidizers, and slag formers. This process was known as Una-Matic and had limited success in the United States.

A similar method was utilized in Europe; the coating was made by extruding small half-circular sections, which were notched and joined together with two small wires, like beads. These were fed in from both sides to the bare electrode wire just above the arc and constituted the covering on the electrode. This process had limited success.

Another system utilized the magnetic field surrounding the electrode wire to carry flux into the arc. The bare electrode wire was fed into the arc, surrounded by carbon dioxide gas which carried powdered magnetic flux. The *magnetic flux* is attracted to the electrode wire by the magnetic field. The magnetic flux covered the electrode wire as it entered the arc. The flux performed the normal function. The carbon dioxide gas also aided in shielding the molten weld metal from the atmosphere. It never became a major welding process, largely due to the problems of feeding and handling the magnetic flux. A system developed in England, which became successful and is still in use, utilizes a *composite electrode*. The composite filler metal electrode is of special design. The large-diameter center core wire is wrapped with small wires spiraled in one direction and small wire-spiraled in the opposite direction, to create cavities. This composite assembly is run through an extrusion press and flux is forced into the cavities to provide protection in the same manner as the covering on a conventional coated electrode. Figure 6-127 shows the construction of this special electrode. The electrode is placed on large coils so that the coating will not crack and separate.

FIGURE 6-127 Details of composite electrode. 1, core wire; 2, small diameter wrapped wire; 3, extruded coating material.





The welding head is conventional except the current pickup jaws are elongated to provide a large contact area to conduct the welding current to the electrode. Various types of flux coverings are available to provide different characteristics or to match different types of carbon and low-alloy steels.

A recent variation uses CO_2 shielding gas to surround the arc area. This provides for higher welding currents and faster travel speeds. Both the unshielded and CO_2 gas shielded processes are limited to the flat and horizontal fillet weld positions. It is used in shipbuilding. This process is not used with semiautomatic equip-

ment since the electrode wire is not sufficiently flexible to be easily manipulated by a welder.

6-10 ARC WELDING VARIABLES

During the manual welding operation the welder has control over certain factors that affect the weld. For example, the welder can increase or decrease the speed of travel along the weld joint. The welder can increase the length of the arc and the voltage or decrease the length of the arc and the voltage. In this way the welder is also changing the welding current. Additionally, the welder can change the angle of the electrode or the torch to either push or drag, and these changes can be made while welding. When all the variables are in proper balance, the welder will have a smooth-running arc and will deposit high-quality weld metal. This section will explain the effect of each of the welding procedure variables on the characteristics of the weld. It will also explain how these variables interrelate and how some of them are more easily changed and are useful for control.

The effect of changing these variables and the resulting change in the weld is essentially the same for all of the arc welding processes in which the weld metal crosses the arc. For those arc welding processes in which the arc is used as a heat source and the metal does not cross the arc, the relationship is slightly different. All welds shown are on steel, however; the basic factors apply to other metals as well.

Welding variables can be divided into three classifications. These are: primary adjustable variables, secondary adjustable variables, and preselected or distinct level variables. The primary adjustable variables are those most commonly used to change the characteristics of the weld. These are: the travel speed, the arc voltage, and the welding current. They can be easily measured and continually adjusted over a wide range. These primary variables control the formation of the weld by influencing the depth of penetration, the bead width, and the bead height (or reinforcement). They also affect deposition rate, arc stability, spatter level, and so on. Specific values are assigned to these primary adjustable variables. They are normally included in welding procedure schedules and can be duplicated time after time.

The *secondary* adjustable variables can also be changed continuously over a wide range. The secondary adjustable variables do not directly affect bead formation; instead, they cause a change in a primary variable which in turn causes the change in weld formation. Secondary adjustable variables are more difficult to measure and accurately control. They are assigned values and are usually included in welding procedure schedules. They include tip-to-work distance (stickout) and electrode or nozzle angle.

The third class of variables is known as *distinct level* variables, since they cannot be changed in a continuous fashion, but normally in increments or in specific steps. Distinct level variables must be preselected and are fixed during a particular weld. They have considerable influence on the weld formation. Distinct level variables that must be preselected are normally included in welding procedure schedules. They include the electrode size, the electrode type, welding current type and polarity, shielding gas composition, and flux type. These variables are selected with regard to the type of metal to be welded, the thickness of the material, joint design, welding position, deposition rate, and appearance.

Primary Adjustable Variables

The primary adjustable variables are welding current, arc voltage, and travel speed. To best explain the effect of these variables, bead on plate welds is shown with the three characteristics involved: weld penetration, the weld width, and the weld reinforcement. Each variable has a distinct effect on the three weld characteristics.

When making welds to establish a welding procedure or in reviewing welds that did not meet requirements, judgment is based on these three weld characteristics. Welding penetration is usually the most important and it is affected by all three of the variables. Penetration is also affected by the secondary adjustable variable and by the preselected variables.

If in analyzing the weld it is decided that penetration must be increased, one of the preselected variables may have to be changed. For example, if the maximum welding current for a particular electrode size is being used, it would be necessary to change to a larger electrode size to further increase the welding current. This same rationale may have to be followed to change the bead width or weld reinforcement if the limit of a primary variable is reached without obtaining the desired results.

Three sets of curves show the effect of the three primary variables on the three weld characteristics. Figure 6-128 shows the effects of the three variables on weld penetration. Penetration is the distance that the fusion zone extends below the original surface of the parts being welded. Joint design is also a factor that must be considered. This curve is based on flux-cored arc welding, but would apply to gas metal arc welding, submerged arc welding, and, to a fairly large degree, to shielded metal arc welding. The values may change, but the relationships are similar. To explain this, Figure 6-129 shows bead appearance and weld cross section of welds made with the flux-cored arc welding process. Welding conditions were $\frac{3}{32}$ in. (2.4 mm) electrode, 29 V, electrode positive, and travel speed 20 in./min (510 mm/min). The depth of penetration increases as the current level increases. The welding current and weld penetration relationship is almost a straight line and is the most effective in controlling this weld characteristic. It should be considered first when a change of penetration is required.

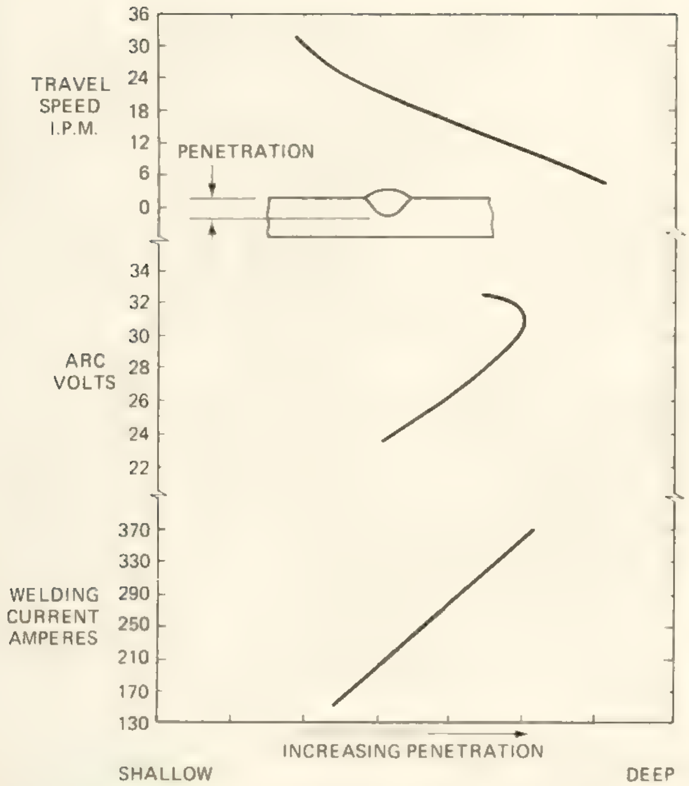


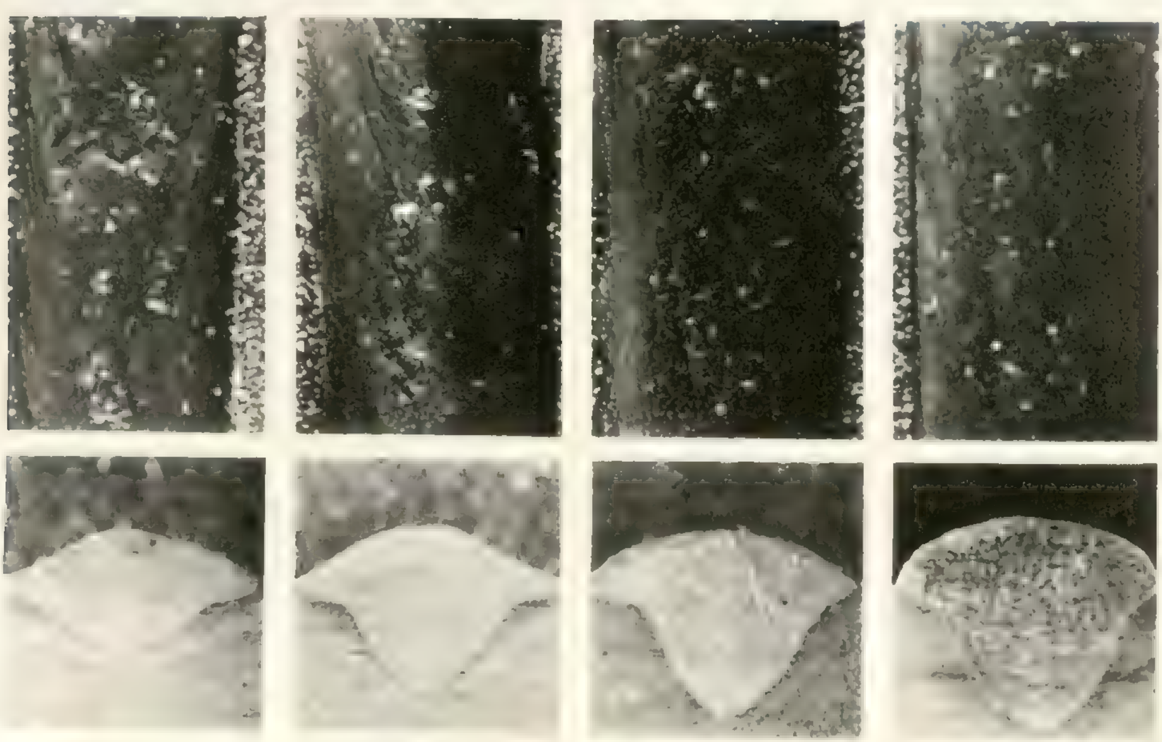
FIGURE 6-128 Weld penetration related to primary variable.

The relationship between travel speed and weld penetration also is a relatively straight line relationship. Penetration is increased as travel speed is decreased. Travel speed should not be used as the major control, since, for economical reasons, it is unusually desired to weld at a maximum speed possible.

The relationship of penetration and arc voltage is not a straight-line relationship. The curve shows that there is an optimum arc voltage where penetration is maximum. Raising or lowering arc voltage from this point reduces penetration. Thus a long arc or a short arc will decrease penetration. For a given welding current there is a certain voltage that will provide the smoothest welding arc. It is for this reason that arc voltage is not recommended as a control for penetration.

The weld bead width relationship to the primary variables is shown in Figure 6-130. Bead width is an important characteristic of a weld, particularly when using automatic equipment to fill a weld groove or to produce a specific geometry of a weld. The arc voltage variable, or arc length, is a straight line relationship with weld bead width. As the arc voltage is increased, bead width increases. This can be explained by considering the welding arc. The welding arc has a point-to-plane relationship and is thus conical in shape with the point of the cone at the end of the electrode and the wide portion at the surface of the weld. This is shown in Figure 6-131

FIGURE 6-129 Weld penetration versus welding current.



400 Amp 450 Amp 500 Amp 550 Amp

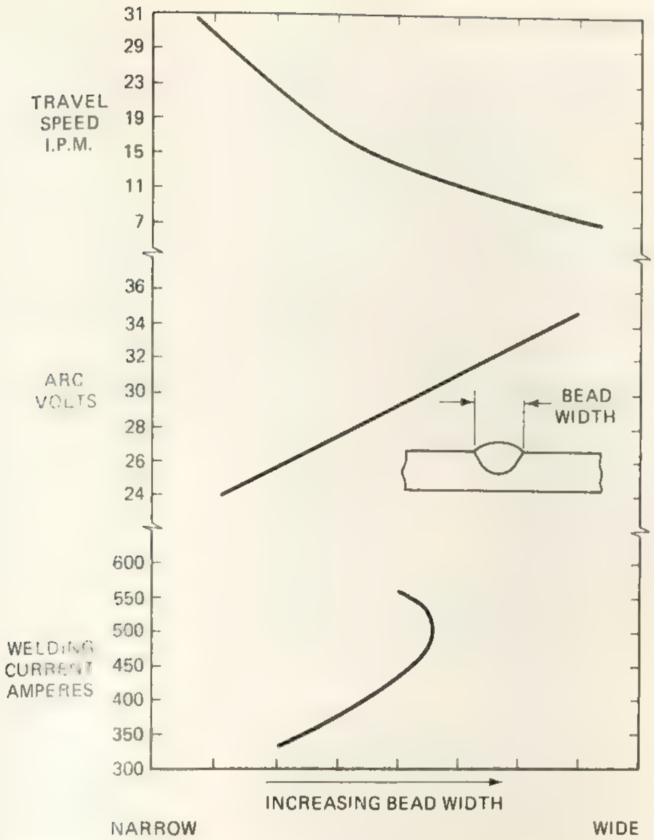


FIGURE 6-130 **Weld bead width related to primary variable.**

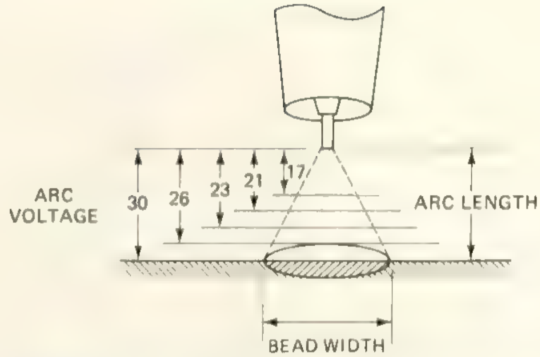
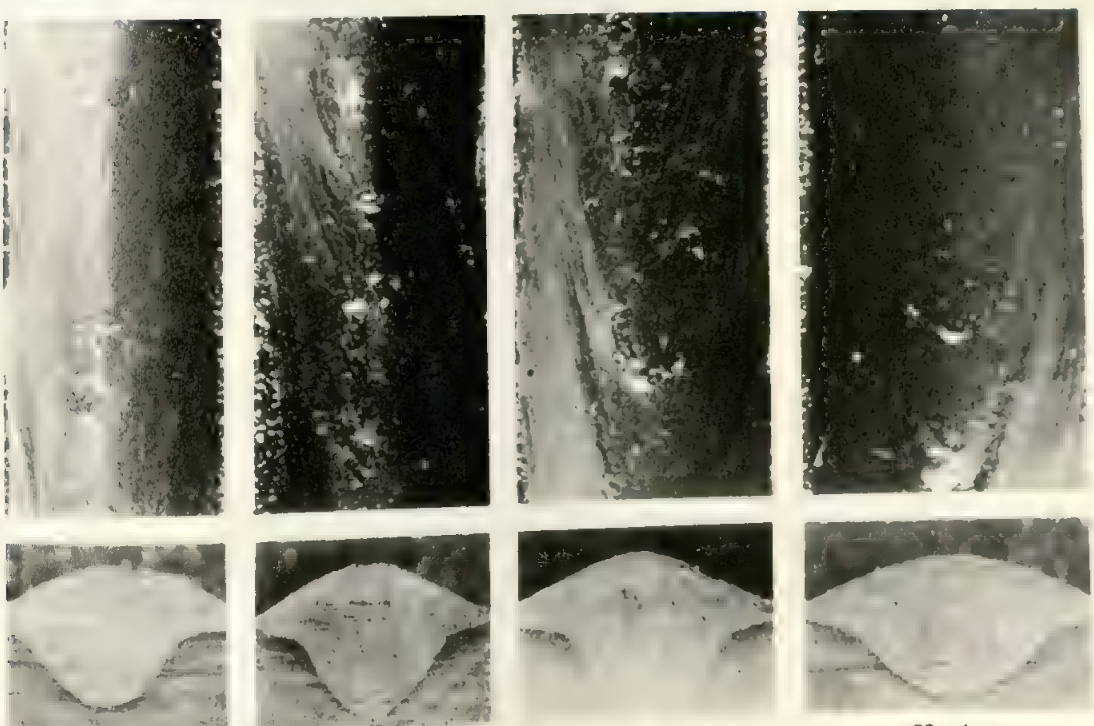


FIGURE 6-131 **Weld bead width related to arc voltage.**

and explains the relationship between the longer arc with higher voltage and the bead width. This shows the arc voltage at different arc lengths and how the arc spreads out and makes a wider bead. This relationship is also shown in Figure 6-132 which shows the weld surface appearance and cross section of flux-cored arc welds made at different arc voltages. Welding conditions: electrode size and travel speed are the same as previously; the current is 450 A. Since increasing the arc voltage makes the bead wider, the reinforcement is reduced because the same volume of weld metal is involved. Conversely, reducing the arc voltage makes the bead narrower and increases the height of the reinforcement.

FIGURE 6-132 **Arc length–weld bead width relationship.**



27 volts 29 volts 31 volts 33 volts

Travel speed is the second choice for changing bead width, since it has a relatively straight line relationship. The welding current is not a straight-line relationship, as is shown by the curve. Therefore, welding current is not used as a control for weld bead width.

The weld bead reinforcement or height related to the three primary variables is shown by the curve of Figure 6-133. Weld reinforcement is important in automatic welding when considering the requirements for filling a groove weld with the proper amount of metal using the desired number of passes. The weld height is most effectively controlled by travel speed because of the relatively straight line relationship. It should be the first choice for changing weld reinforcement.

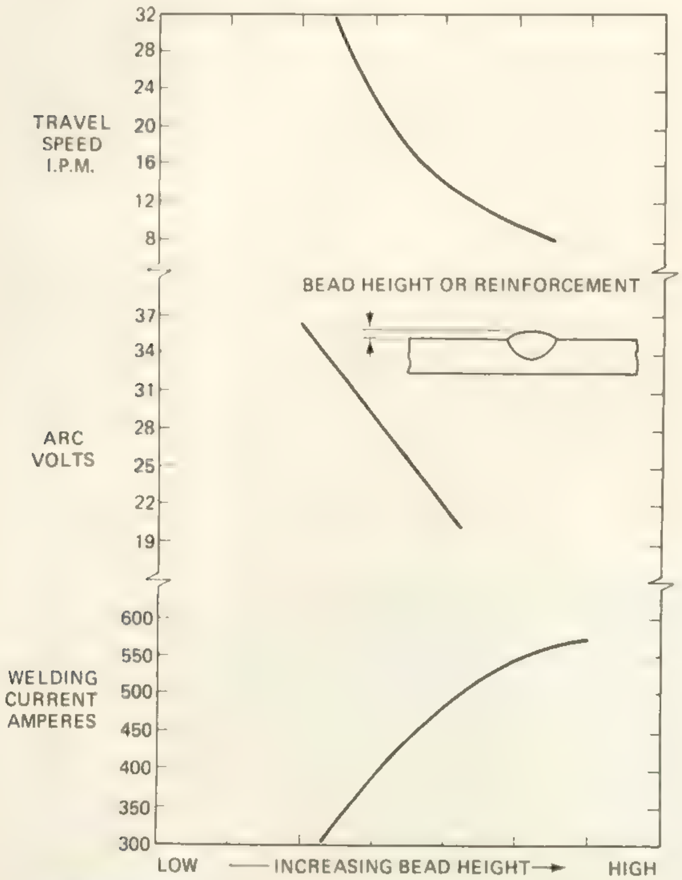


FIGURE 6-133 Weld bead reinforcement related to primary variable.

The welding current to bead height is a relatively straight line relationship. This is based on the mass or amount of weld metal deposited. The travel speed relationship to the weld characteristics is shown in Figure 6-134, which shows the weld surface appearance and cross section of flux-cored arc welds made at different speeds. Welding conditions: electrode size is the same as for the previous welding; current, 450 A, voltage, 29 V. At the lower travel speeds the weld is large in mass, whereas at the high travel speed it is smaller in mass. This relationship is very easily determined by relating the cross-sectional area of the welding electrode times the wire feed speed to the cross-sectional area of the weld times the travel speed. As more electrode is fed into the arc, based on higher welding current, a greater mass of metal is deposited. However, as the speed of travel is increased, this mass of metal will be spread out over a longer length. The relationships shown relate penetration, bead width, and reinforcement to welding current, arc voltage, and travel speed. Notice the interaction that occurs. These relationships can only be varied within limits, since there is a relatively fixed relationship between arc voltage and welding current within the stable operating range. This relationship changes for different processes, shielding-gas atmospheres, and electrode sizes. The relationship is shown in Figure 6-135 for flux-cored arc welding.

All these relationships are relative. Different values would be used for different processes. The shape of the curves and the changes in weld bead characteristics would be the same.

Secondary Adjustable Variables

The secondary adjustable variables include at least the stickout and torch or electrode angle. These variables change the weld characteristics because they influence one of the primary variables. When using the CV welding system, welding current is controlled by the electrode wire feed speed. Therefore, penetration is directly influenced by wire feed speed when all other conditions are the same. Since welding current can be easily measured, penetration is normally related to it rather than to wire feed speed. The wire feed speed–current relationship can be changed by changing polarity, shielding media, electrode wire size, and the stickout. Stickout is shown in Figure 6-136. It is in this area where preheating of the electrode occurs and it is sometimes called I^2R heating. This is because the electrode wire extending from the current pickup tip to the arc is heated by the tremendous amount of current being carried by the wire. The heat generated in this portion of the electrode wire is equal to I^2R , which is the current squared times the resistance of the electrode wire. This preheats the electrode wire so that when it enters the arc it is at an elevated temperature, which increases the melt-off rate. Increasing stickout increases deposition rate *only if the wire feed speed is increased* sufficiently to maintain the current at a constant value (Figure 6-137). Extended nozzles with insulated guide tubes are used to create *electrical stickout*, which preheats the wire. This factor is used in gas metal arc, submerged arc, and flux-cored arc welding to increase the deposition rate.

The relationship between stickout and welding current is shown in Figure 6-138. Increasing the stickout will reduce the welding current in the arc by almost 100 A when the wire feed speed rate is not changed. This re-

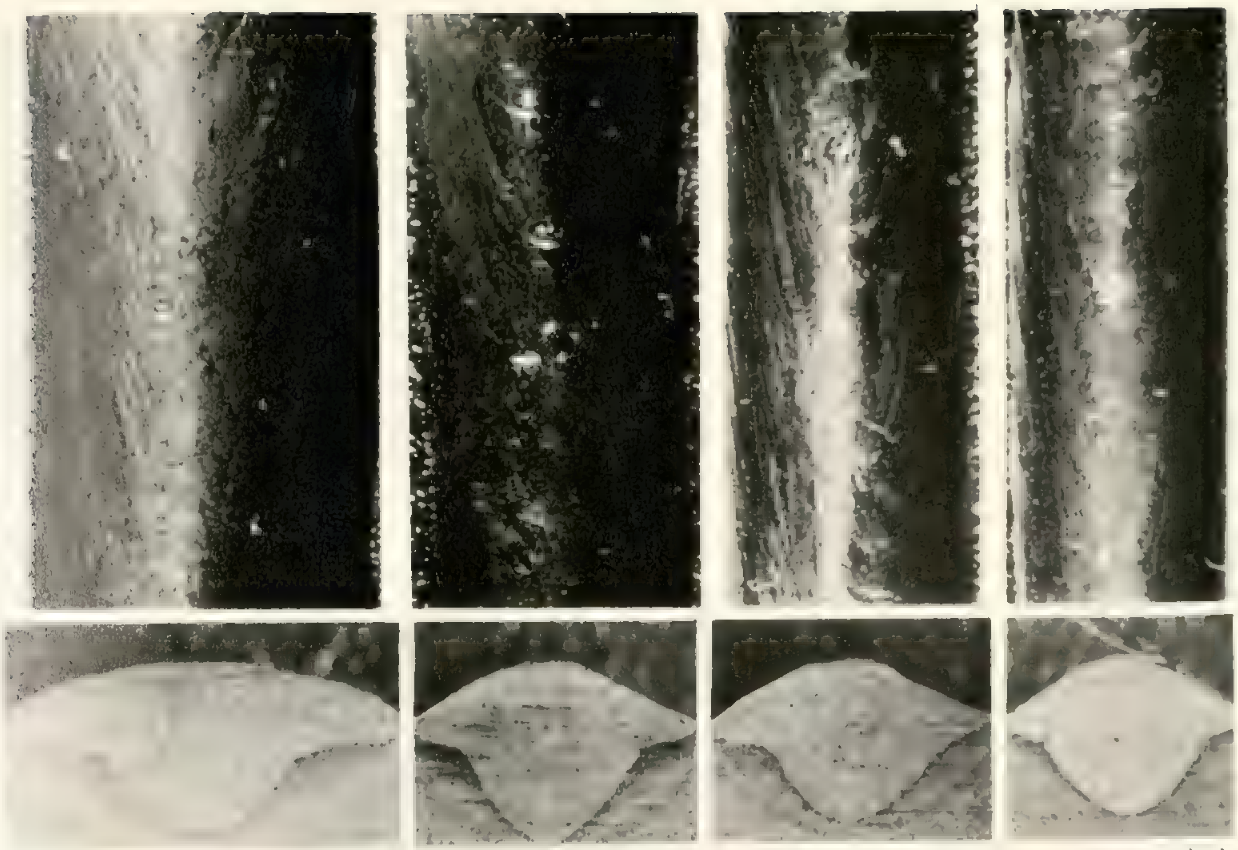


FIGURE 6-134 Weld bead related to travel speed.

FIGURE 6-135 Welding voltage–current relationship.

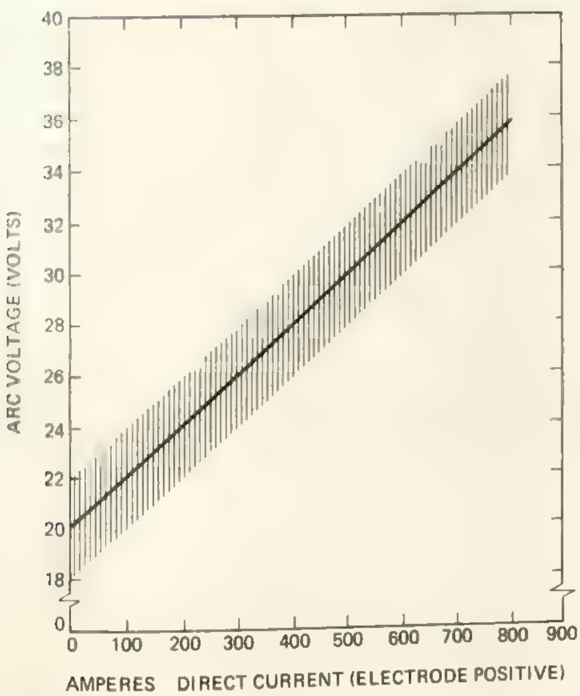
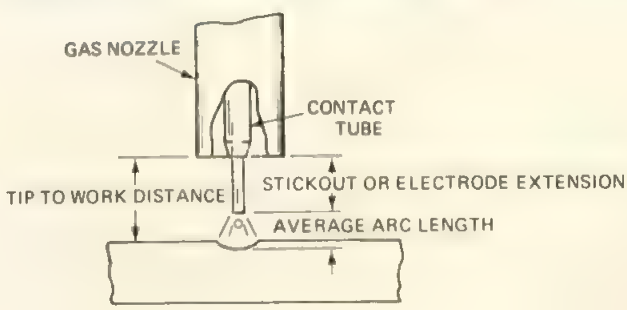


FIGURE 6-136 Stickout or electrode extension.



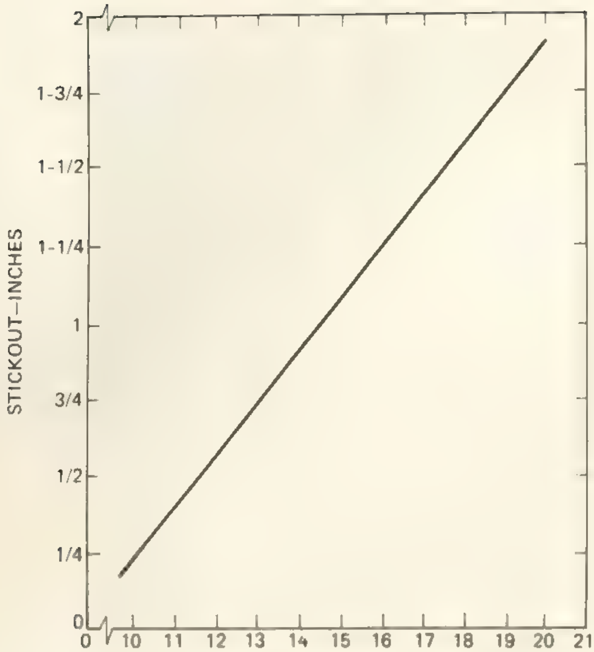
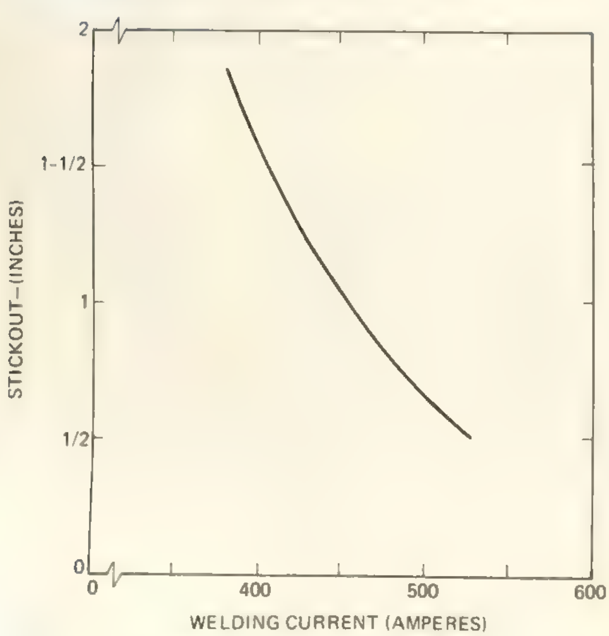


FIGURE 6-137 **Stickout versus deposition rate.**

duces penetration a proportional amount. In semiautomatic welding, the stickout is adjusted by the welder and is an excellent means of compensating for joint variations without stopping the weld. Stickout exerts an influence on penetration through its effect on welding current (Figure 6-139). Stickout is thus a control during the welding operation.

Stickout influences the welding current. Increasing

FIGURE 6-138 **Stickout versus welding current.**



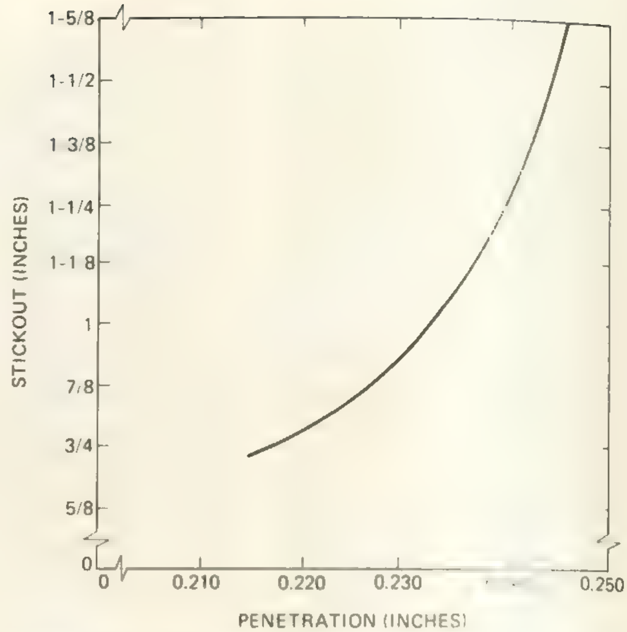


FIGURE 6-139 **Stickout versus penetration.**

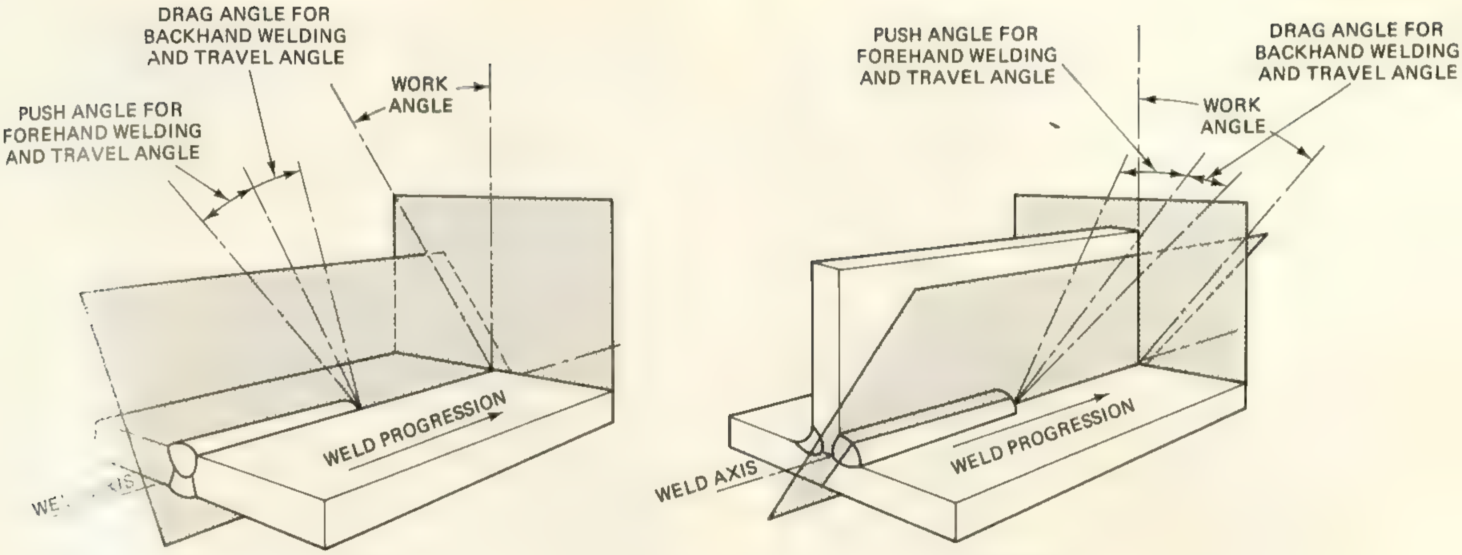
the electrode extension increases the resistance in the circuit and with the voltage constant the current will be reduced in accordance with Ohm's law. The voltage between the current pickup tip and the work is the sum of the voltage across the arc and the voltage drop in the electrode extension. As the electrode extension or stickout increases, the circuit resistance increases and the welding current decreases. The output voltage of the power source remains constant; therefore, more voltage occurs across the extension and thus less voltage occurs across the arc. The decrease of both voltage and current will reduce the penetration of the arc.

Conversely, as the stickout (electrode extension) decreases, the preheating effect is reduced and the welding power source furnishes more current. This increase in welding current provides a proportionate increase in penetration.

Another secondary adjustable variable is the electrode or nozzle travel angle, which has an appreciable effect on penetration. Two angles are required to define the position of an electrode or welding gun nozzle: (1) the travel angle, and (2) the work angle.

The work angle is the angle, less than 90°, between a line perpendicular to the major workpiece surface and a plane determined by the electrode or centerline of the welding gun and the weld axis. In a T-joint or a corner joint the line is perpendicular to the nonbutting member (Figure 6-140).

The travel angle is the angle, less than 90°, between the electrode centerline, or centerline of the welding gun, and the line perpendicular to the weld axis, in a plane determined by the electrode axis and the weld axis. This is also shown in Figure 6-140.



(a) GROOVE WELD (b) FILLET WELD

FIGURE 6-140 **Travel and work angles: groove and fillet welds.**

The travel angle is described further as being either a drag angle or a push angle. The drag angle is the travel angle when the electrode is pointing in a direction opposite to the progression of welding (points backward). The push angle is the travel angle when the electrode is pointing in the direction of weld progression (point forward). The push angle is also known as forehand welding, and the drag angle is also known as backhand welding.

In pipe welding, the work angle is the angle, less than 90°, between a line that is perpendicular to the pipe surface at the point of intersection of the weld axis and the centerline of the electrode or welding gun, and a plane determined by the centerline of the electrode and a line tangent to the pipe at this same point (Figure 6-141). The travel angle for a pipe weld is the angle, less than 90°, in the electrode centerline or the torch centerline and a line perpendicular to the weld axis at its point of intersection with the electrode centerline, in a plane determined by the electrode centerline and a line tangent to the pipe surface at the same point. This is also shown.

It is found that maximum penetration is obtained when a drag angle of 15 to 20° is used. If the gun travel angle is changed from this optimum condition, penetration decreases. From a drag angle of 15° to a push angle of 30° the relationship between penetration and travel angle is almost a straight line. Therefore, good control of penetration can be obtained in this range. It is not recommended that a drag angle greater than 25° be used. The gun travel angle variable can also be used to change bead height and width, since the gun travel angle does affect bead contour. A drag travel angle tends to produce a high, narrow bead. As the drag angle is reduced,

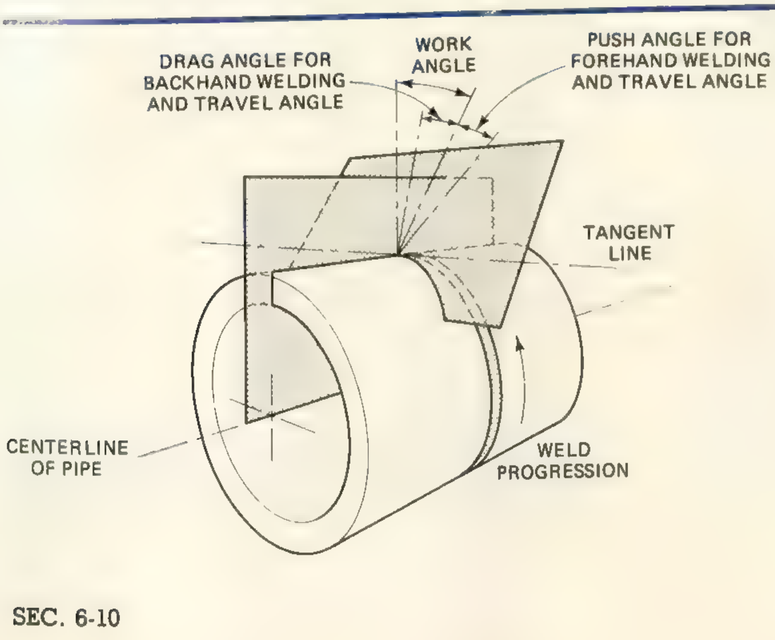


FIGURE 6-141 **Travel and work angles: pipe welding.**

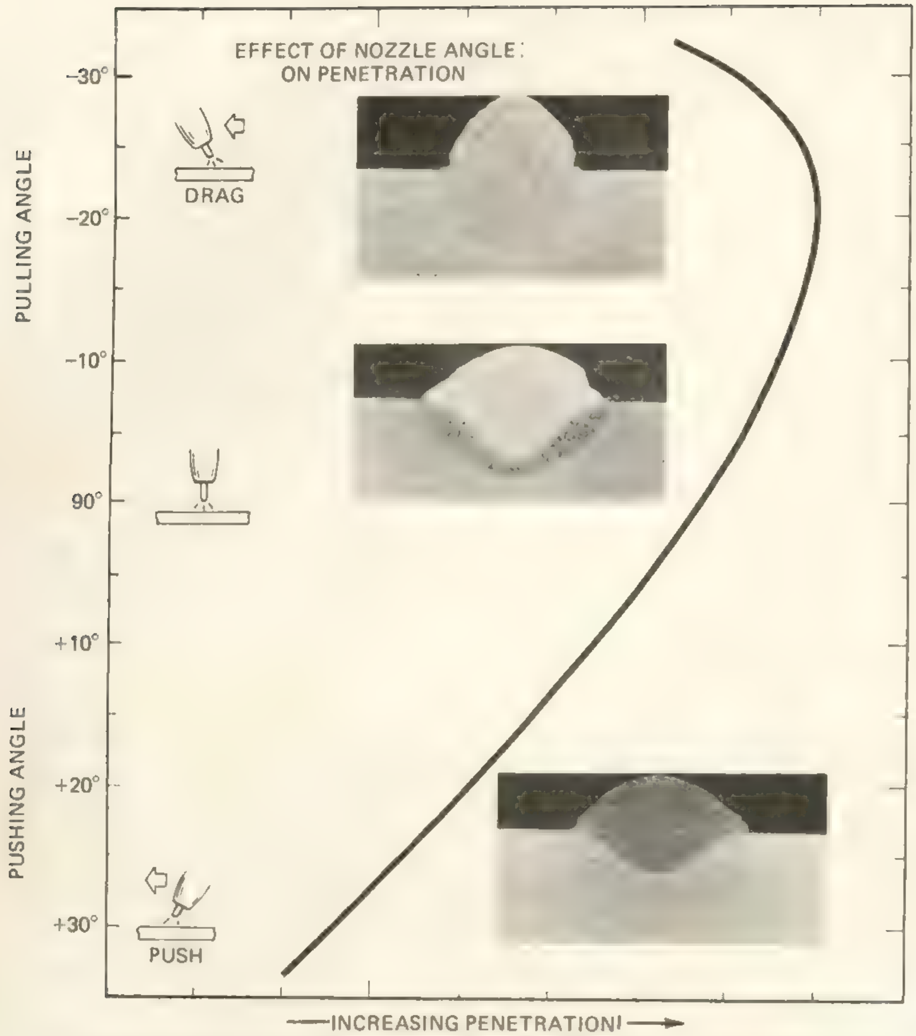


FIGURE 6-142 Travel angle versus penetration.

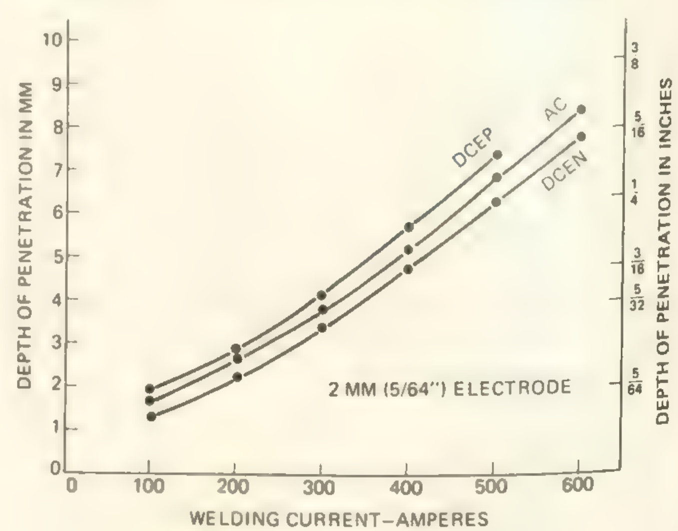
the bead height decreases and the width increases. This relationship is shown by Figure 6-142. The push travel angle is used for high travel speeds. These angles vary slightly with different processes and procedures.

Distinct Level Variables

The most important distinct level variable is the selection of the welding process. Once this is done the next important variable can be the polarity of welding. In general, direct-current electrode positive DCEP produces greater penetration than electrode negative DCEN. Alternating current, which is used only with submerged arc welding, produces penetration between that produced by electrode positive and electrode negative. The polarity of the electrode and its influence on penetration is shown by the three curves in Figure 6-143. This is also shown by Figure 6-144, which was made using the submerged arc welding process.

The other variable has to do with electrode size. Smaller size electrodes tend to produce deeper penetration. This is related to the geometry of the arc and the

FIGURE 6-143 Welding polarity versus penetration: curve.



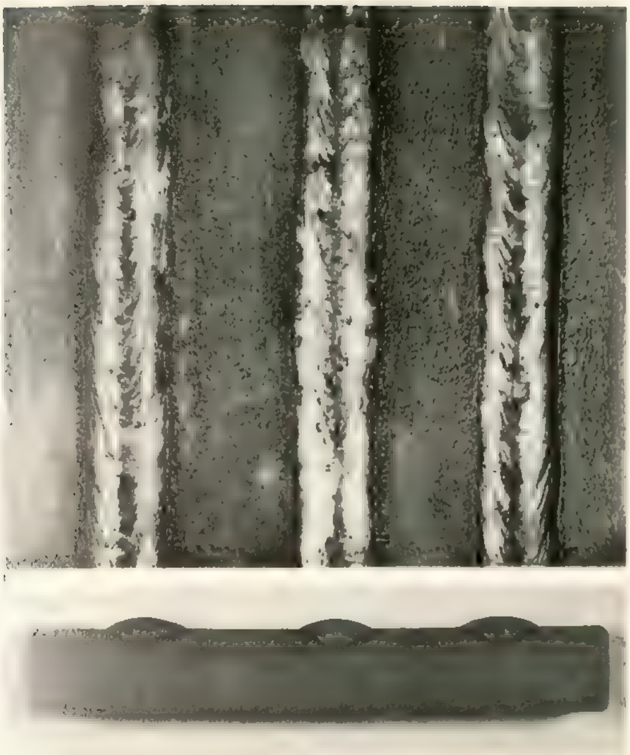


FIGURE 6-144 Welding polarity versus penetration: cross section.

point-to-plane relationship. The higher the current density on the electrode wire, the deeper the penetration. Larger-wire electrodes produce wider beads and less penetration (Figure 6-145).

In gas metal arc and flux-cored arc welding, the use of CO_2 gas shielding provides deeper penetration. It is the characteristic of carbon dioxide to provide deep penetration. The shielding gas relationship to penetration is shown in Figure 6-146, made using a self-shielding flux-cored electrode wire.

Also, in gas metal arc welding the type of shielding gas affects the weld bead shape and penetration pattern. Argon has a characteristic deep center or pointed penetration, while CO_2 provides a wider pattern. The CO_2–argon mixture is between these. The cross-sectional view and weld surface appearances are shown in Figure 6-147.

FIGURE 6-145 Electrode size versus penetration.

FIGURE 6-146 With and without shielding gas (FCAW).

FIGURE 6-147 Shielding gas versus weld bead shape.

Change Required	Welding Variable	Arc Voltage	Welding Current (Feed Speed)	Travel Speed	Travel Angle	Stick-out or Tip-to-Work Distance	Electrode Size
Deeper penetration			[1]Increase		[3]Drag max. 25°	[2]Decrease	[5]Smaller*
Shaller penetration			[1]Decrease		[3]Push	[2]Increase	[5]Larger*
Bead height and Bead width	Larger bead		[1]Increase	[2]Decrease		[3]Increase*	
	Smaller bead		[1]Decrease	[2]Increase		[3]Decrease*	
	Higher narrower bead	[1]Decrease			[2]Drag trailing	[3]Increase	
	Flatter wider bead	[1]Increase			[2]90°	[3]Decrease	
Faster deposition rate			[1]Increase			[2]Increase*	[3]Smaller
Slower deposition rate			[1]Decrease			[2]Decrease*	[3]Larger

Key: 1 First choice, 2 Second choice, 3 Third choice, 4 Fourth choice, 5 Fifth choice.

*It is assumed that the wire feed speed is readjusted to hold welding current constant.

FIGURE 6-148 **Recommended variable adjustments for consumable electrode arc welding.**

By fully understanding the relationship of the variables and their effect on weld characteristics, it is possible to establish a welding procedure to provide the exact type, shape, size of weld, and welding production rate that are required. A summary of the welding variables that can be changed to change the characteristics of the weld is given in Figure 6-148.

6-11 ARC WELDING PROCESS SELECTION

The criteria for selecting an arc welding process is extremely complex. In view of this complexity, it is well to establish a basis for choosing the welding process. There are a number of factors that must be considered. These can be summarized as follows:

1. The ability to join the metals involved
2. The quality or reliabilty of the resulting joint
3. The capability of the process to join the metals in the thickness and position required
4. The most economical way of joining metals
5. The availability of the necessary equipment
6. The familiarity of the personnel involved in making the joint
7. Other factors, such as the engineering capabilities to design, the user reaction to the method, and so on.

The ability to join the given material must be the very first consideration. In many cases the material can be welded with a number of welding processes; then the selection depends on other factors. The quality or reliability of the joint produced by the processes is the second basis for process determination. The designer must be completely aware of the quality requirement of the product, which involves the service requirements, specifications, codes, and environmental exposure that can be expected. The materials to be joined must be selected on the same basis. It is then necessary to determine the metals joining process that will provide a joint of the same quality. Each of the arc welding process sections discusses the quality aspects of the weld produced by that process. This becomes the basis for selection decision.

The third factor to consider is the thickness of the metals to be joined and the positions of the work or joints to be welded. In addition, some processes have all-position capabilities, while others are limited to one or a few welding positions. This information is summarized in Figure 6-149. The position capability may not be as important since many products or assemblies can be positioned to place them in the proper position for most advantageous welding. There are some situations where the position cannot be altered, for example in the field erec-

Welding Position	Welding Process Rating			
	SAW	GMAW	FCAW	ESW
1. Flat	A	A	A	No
Horizontal fillet	A	A	A	No
2. Horizontal	C	A	A	No
3. Vertical	No	A	A	A
4. Overhead	No	A	A	No
5. Pipe-fixed	No	A	A	No

FIGURE 6-149 Summary of welding positions for consumable electrodes.

tion of large products and in the repair welding of products that cannot be moved.

In all of the arc welding sections a description has been presented showing the capabilities of the process for welding various thicknesses of metals.

The three factors above will narrow down the choice of welding processes available. After analyzing these three, there still is the requirement to eliminate all processes but one in order to establish the optimum and most economical welding process. The welding cost factor should then be used. The two major components in welding cost are the cost of labor to apply the welds and the cost of the materials used.

The cost of labor has continually increased and will continue to increase. It is therefore important to utilize processes that are most productive and can be used most efficiently. The productivity of a welding process is related to its depostion rates. Deposition rate data for each of the processes are presented in the process section; however, a summary of depostion rates based on 100% duty cycle is shown in Figure 6-150. This data is an indication and is not the entire story. Certain processes provide high deposition rates but may require more weld metal to complete the weld joint. Joint design and the amount of metal required to make the weld joint enter into this. Process productivity relates to labor cost, since each process may be applied in more than one way. The method of applying the continuous electrode wire processes is summarized in Figure 6-151. Each of the methods of applying has a specific operator factor or duty cycle based upon the amount of time that the process is in actual operation depositing metal, versus the time available. The approximate operator factor related to the method of application is shown in Chapter 28.

The other factor has to do with cost of materials. To assist in this, it is important to recognize that all filler metals are not utilized to the same degree. The amount of filler metal purchased is not all to be deposited in the weld joint. The filler metal with the lowest utilization is the covered electrode used for shielded metal arc welding. Only about 65% of the weight of the electrodes purchased becomes deposited weld metal in the product. For the nonconsumable electrode processes the amount of filler metal purchased verus that deposited will approach 100%. In gas metal arc welding and electroslag welding the amount of purchased weld metal deposited in the joint is 95% while the amount of flux-cored electrode wire deposited in the joint approaches 85%.

Another factor that affects the cost of welding has to do with the number of pieces or parts or the amount of identical welding that is to be done to meet production requirements. The volume of production has a great bearing on the cost of welding and must be involved in the selection of the process.

The availability of the equipment to produce the product also has a bearing on the process selection. Products similar to those normally produced will utilize the same manufacturing process and there is no need to consider different equipment. If the new item is sufficiently different from existing products its production will require more equipment or will possibly utilize existing idle equipment. The cost and the availability of the equipment are important factors. Tooling for high-volume production or specialized precision welding must also be considered.

It is important to be objective and question whether or not the availability of equipment overweighs new equipment that might be more productive. Changing to a more productive welding process can make available equipment obsolete. Perhaps this can be justified by a quick repayment of the cost of the new equipment.

The familiarity of the personnel can have an important bearing on process selection. If new processes are adopted, it may be necessary to provide a training program to teach existing personnel new skills. If the price of the training is such that the overall total expense will be less it is best to provide the training and adopt the new process. A transition of this type can be very difficult because it will affect labor relations. An objective view should be taken to compare the availabilty of skill of the existing work force versus what would be required if the process were changed. It is necessary to consider inspection, material preparation, and supervisory and administrative personnel, as well.

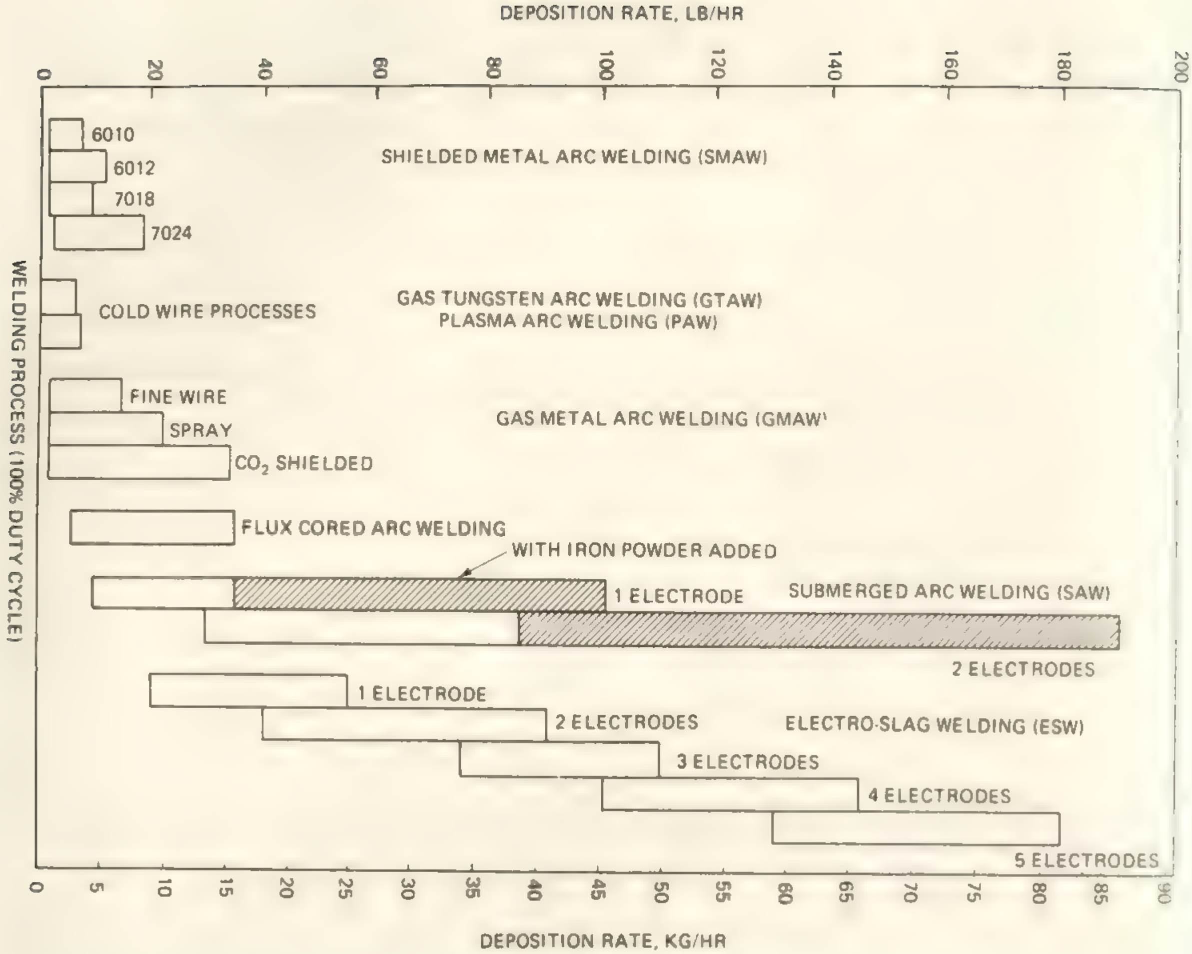


FIGURE 6-150 Deposition rate summary by welding process using consumable electrode.

FIGURE 6-151 Summary of methods of application.

Method of Applying	Welding Process Use			
	SAW	GMAW	FCAW	ESW
Manual (MA)	Not used	Not used	Not used	Not used
Semiautomatic (SA)	Not popular	Most popular	Most popular	Not used
Machine (ME)	Most popular	Most popular	Most popular	Most popular
Automatic (AU) and automated	Most popular	Most popular	Most popular	Most Popular

There are several other factors that must be considered. A very important one has to do with the ability of engineering and design personnel to adopt to a new process. There is reluctance to switch from one well-known process to a new unknown one. Another factor has to do with the user of the end product. Users are familiar and apparently satisfied with the present method of production. Change can upset relationships and cause users to discontinue the product which is made by a new process. When suddenly confronted with a welded assembly they may have questions concerning the new part and its ability to withstand the rough service. There is also the reluctance to change versus the necessity to improve products and reduce production costs.

When all these factors are considered, a manageable plan evolves. It will enable the metalworking engineer or executive to chart a course with the known factors and to arrive at the preferred welding process. Alternative selections may result and practical production tests should be made to obtain the final answer.

QUESTIONS

6-1. Is CO_2 shielding gas used for GMAW welding of aluminum?

6-2. What is the main purpose of the coating on stick electrodes?

6-3. What are three types of metal transfer in an arc welding process?

6-4. What is the main purpose of submerged arc flux? Other purposes?

6-5. Why isn't submerged arc welding an all-position welding process?

6-6. If ac is used for submerged arc, is it CC or CV?

6-7. Is a welding helmet required for submerged arc welding?

6-8. For gas metal arc welding, what changes are required in weld joint design?

6-9. Describe the electrogas process of welding. For what position is it used?

6-10. When is cooling water recommended for the GMAW torch or gun?

6-11. What is the major difference between FCAW and GMAW?

6-12. What equipment changes are necessary to change processes?

6-13. What are the three classifications of welding variables?

6-14. What adjustments change weld penetration? Explain.

6-15. What adjustments change weld bead width? Explain.

6-16. What adjustments change weld bead reinforcement? Explain.

6-17. What is stickout, and what effect does it have?

6-18. Define "work angle" and "travel angle."

6-19. What makes electroslag welding different from submerged arc welding?

6-20. What welding groove design is normally used for electroslag welding?

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7

Gas Welding, Brazing, Soldering, and Solid-State Welding

OUTLINE

7-1 OXYFUEL GAS WELDING

Oxyfuel gas welding (OFW) is a group of welding processes that produce coalescence of workpieces by heating them with an oxyfuel gas flame. The processes are used with or without the application of pressure, and with or without the filler metal. There are three major processes within this group: oxyacetylene welding, oxyhydrogen welding, and pressure gas welding. There is another process, but of minor industrial significance, known as air-acetylene welding. In this process heat is obtained from the combustion of acetylene with air.

The most popular process in this group is oxyacetylene welding, which is an oxyfuel gas welding process that uses acetylene as the fuel gas. The process is used without the application of pressure. Oxyhydrogen welding (OHW) is an oxyfuel gas welding process that uses hydrogen as the fuel gas. The process is used without the application of pressure. The third major process is pressure gas welding (PGW), which is an oxyfuel gas welding process that produces coalescence simultaneously over the

entire faying surfaces. The process is used with the application of pressure and without filler metal.

Oxyacetylene Welding

The oxyacetylene welding (OAW) process (Figures 7-1 and 7-2) consists of high-temperature flame produced by the combustion of acetylene with oxygen and directed by a torch. The intense heat of the flame 6300 °F (3482 °C) melts the surface of the base metal to form a molten puddle. Filler metal is added to fill gaps or grooves. As the flame moves along the joint, the melted base metal and filler metal solidify to produce the weld.

The temperature of the oxyacetylene flame is not uniform throughout its length and the combustion is also different in different parts of the flame. Figure 7-3 shows the temperature in different portions of the flame. The temperature is the highest just beyond the end of the inner cone and decreases gradually toward the end of the flame. The maximum temperature with the other fuel gases is also shown. The chemical reaction for a 1:1 ratio of acetylene and oxygen plus air is as follows:

FIGURE 7-1 Oxyacetylene welding process.

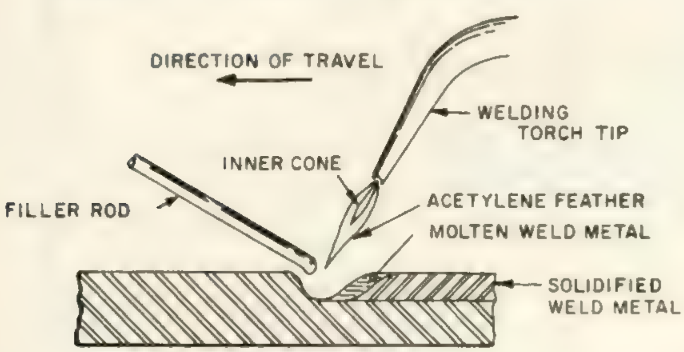
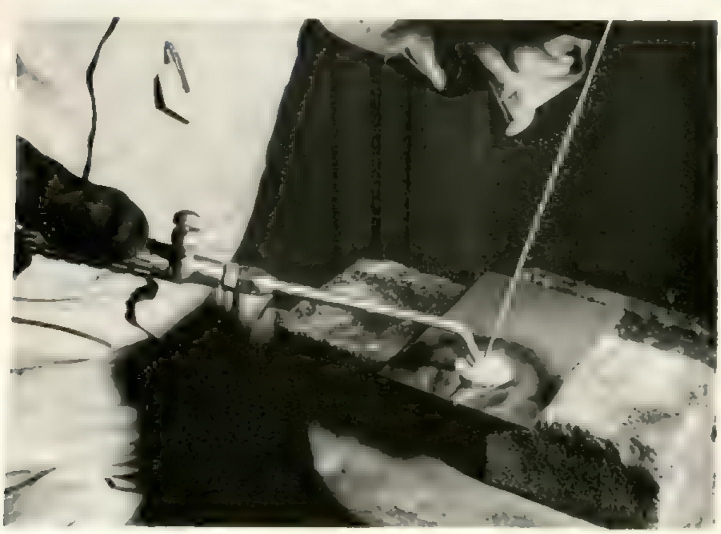


FIGURE 7-2 Using the oxyacetylene welding process.



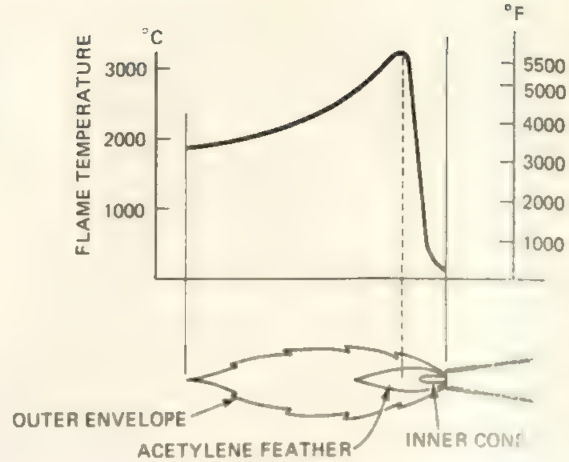


FIGURE 7-3 Temperature of the oxyacetylene flame.

$$C_2H_2 + O_2 = 2CO + H_2 + \text{heat}$$

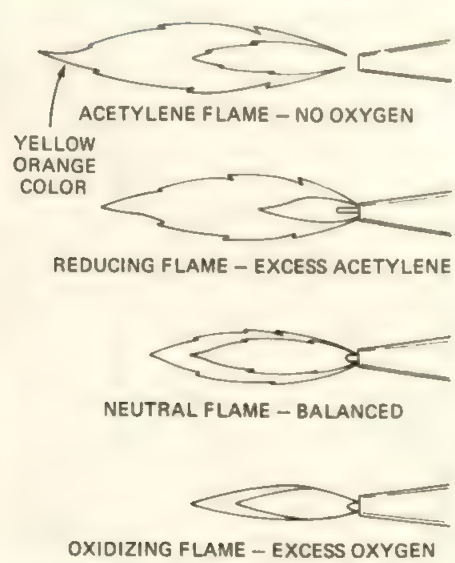
This is the primary reaction; however, both carbon monoxide and hydrogen are combustible and will react with oxygen from the air:

$$2CO + H_2 + 1.5O_2 = 2CO_2 + H_2O + \text{heat}$$

This is the secondary reaction, which produces carbon dioxide, heat, and water.

There are three basic flame types: neutral (or balanced), excess acetylene (carborizing), and excess oxygen (oxidizing) (Figure 7-4). The neutral flame has a 1:1 ratio of acetylene and oxygen. It obtains additional oxygen from the air and provides complete combustion. It is generally preferred for welding. The neutral flame has a clear, well-defined, or luminous cone, indicating that combustion is complete. The carborizing flame has ex-

FIGURE 7-4 Four types of flames.



cess acetylene. This is indicated in the flame when the inner cone has a feathery edge extending beyond it. This white feather is called the acetylene feather. If the acetylene feather is twice as long as the inner cone, it is known as a 2X flame, which is a way of expressing the amount of excess acetylene. The carborizing flame may add carbon to the weld metal. The oxidizing flame, which has an excess of oxygen, has a shorter envelope and a small pointed white cone. The reduction in length of the inner core is a measure of excess oxygen. This flame tends to oxidize the weld metal and is used only for welding specific metals. Most welding procedures use the neutral flame. The welder soon learns proper flame adjustment.

Advantages and Major Uses

The oxyacetylene welding process has the following advantages. The equipment is very portable. It is relatively inexpensive, it can be used in all welding positions, and the puddle is visible to the welder. The equipment is versatile. It can be used for welding, brazing, soldering, and with proper equipment, for flame cutting. It can also be used as a source of heat for bending, forming, straightening, hardening, and so on.

The oxyacetylene welding process is normally used as a manual process. It can be mechanized, but this is not too common. It is rarely used for semiautomatic applications. Oxyacetylene welding is used for welding most of the common metals (Figure 7-5).

When welding any metal, the appropriate filler material must be selected and used. The filler metal must match the composition of the base metal to be welded and normally contains deoxidizers to aid in producing sound welds. Flux is also required for welding certain materials.

The oxyacetylene welding process is normally used for welding thinner materials up to ¼ in. (6.4 mm) thick. It can be used for welding heavier material but is rarely used for thick metals. Its major industrial applications are in the field of maintenance and repair, the welding of small-diameter pipe, and for light manufacturing.

Welding Apparatus

The apparatus and equipment employed for oxyacetylene welding are shown in Figure 7-6. This diagram shows the (1) welding torch and tips, (2) oxygen and acetylene hose, (3) oxygen and acetylene regulators, (4) oxygen cylinder, and (5) acetylene cylinder. A spark lighter is normally used. The welding torch, sometimes called a *blow pipe*, is the major piece of equipment for this process. It performs the function of mixing the fuel gas with oxygen and provides the required type of flame, which is directed as desired. The torch consists of a handle or body, which contains the hose connections for the oxygen and the fuel gas. It also contains an oxygen and acetylene valve for regulating gas flow and a mixing chamber. Various-sized tips can be attached. The torch must be well constructed and rugged, since it is in contact with the high-temperature flame and is expected to have a long life.

There are two basic types of torches, the medium-pressure torch, which is most popular, and the low-pressure or injector type. When using the medium-pressure torch both oxygen and acetylene are supplied at approximately the same pressure, which may vary from 1 to 10 psi depending on the size of the tip being used. The two gases are mixed together in the mixing chamber in the torch handle. Some torches have the mixing chamber in the tip (Figure 7-7).

The injector type of torch uses acetylene at pressures less than 1 psi and are designed so that the oxygen at a higher pressure draws the acetylene into the mixing chamber. Any change in oxygen flow will produce a relative change in acetylene flow so that the proportion of the two gases remains constant.

The valves on the body of the torch control the

Base Metal	Filler Metal Type	Flame Type	Flux Type
Aluminums	Match base metal	Slightly reducing	Al. flux
Brasses	Navy brass	Slightly oxidizing	Borax flux
Bronzes	Copper tin	Slightly oxidizing	Borax flux
Copper	Copper	Neutral	None
Copper nickel	Copper nickel	Reducing	None
Inconel	Match base metal	Slightly reducing	Fluoride flux
Iron, cast	Cast iron	Neutral	Borax flux
Iron, wrought	Steel	Neutral	None
Lead	Lead	Slightly reducing	None
Monel	Match base metal	Slightly reducing	Monel flux
Nickel	Nickel	Slightly reducing	None
Nickel silver	Nickel silver	Reducing	None
Steel, low alloy	Steel	Slightly reducing	None
Steel, high carbon	Steel	Reducing	None
Steel, low carbon	Steel	Neutral	None
Steel, medium carbon	Steel	Slightly reducing	None
Steel, stainless	Match base metal	Slightly reducing	SS flux

FIGURE 7-5 Base metals weldable by the oxyacetylene process.

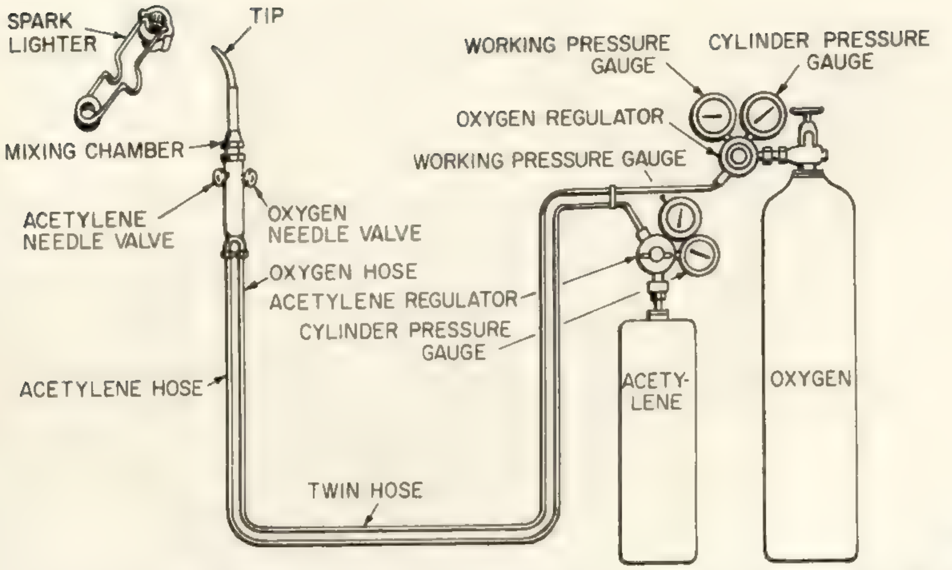


FIGURE 7-6 Apparatus required for welding with OA

amount of oxygen and acetylene or fuel gas which flows to the mixing chamber, where they are combined. Different welding tips are available so that the same torch handle can be used for a wide variety of operations.

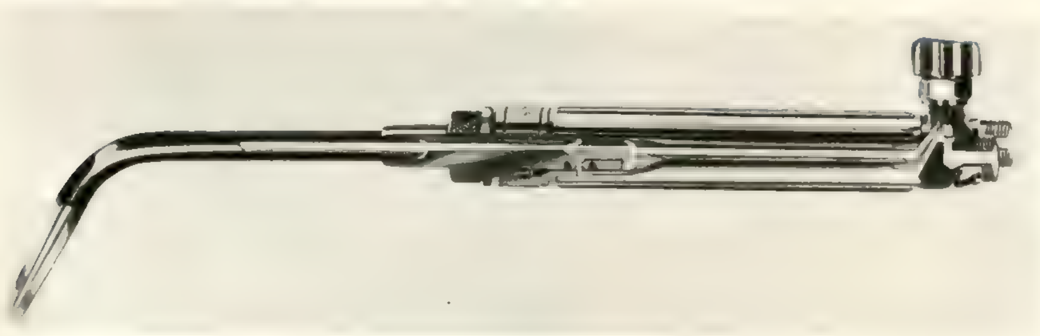
Welding tips are available in a variety of sizes, which are determined by the drill size of the orifice or hole in the flame end of the tip. The larger tip will have a larger orifice, which will produce a larger flame and use more gas. The larger flame supplies greater amounts of heat. The proper tip size must be selected for welding different metals and metal thicknesses. Welding procedure schedules indicate the tip size and gas pressures to be employed. This will determine the volume of gases used. Tips must fit properly and tight to the torch. They must be kept clean for proper operation. Some welding torches are designed so that they can be converted to an oxyacetylene flame cutting torch by replacing the welding tip with a cutting attachment.

The connections for oxygen and acetylene or fuel gas hoses to the torch handle have special threads so that they cannot be incorrectly attached. The oxygen fittings have right-hand threads and the acetylene or fuel gas fittings have left-hand threads. There is a special sequence for opening and closing valves and lighting the torch, which must be followed for safe operation.

Gas pressure regulators are required, for both the oxygen and acetylene. Regulators reduce the pressure of the gas in the cylinder or supply system to the pressure used in the torch. The pressure in an oxygen cylinder can be as high as 2200 psi (15.2 MPa) and this must be reduced to a working pressure of from 1 to 25 psi. (6.9 to 172 KPa.) The pressure of acetylene in an acetylene cylinder can be as high as 250 psi (1.7 MPa) and this must be reduced to a working pressure of from 1 to 12 psi (6.9 to 82 KPa). When gases are piped to the workstations from a central supply, the pressure is lower than above but regulators are still required. A gas pressure regulator will automatically deliver a constant volume of gas to the torch at the adjusted working pressure. The regulators for oxygen and for acetylene and for liquid petroleum fuel gases are of different construction. They must be used only for the gas for which they are designed.

There are two types of regulators, the single-stage regulator and the two-stage regulator. The *single-stage regulator* reduces the cylinder pressure of the gas to a working pressure in one step. Single-stage regulators must

FIGURE 7-7 Medium-pressure oxyacetylene torch.



be readjusted from time to time to maintain the required working pressure. The gas pressure in the cylinder decreases gradually as gas is withdrawn. Single-stage regulators are less expensive than two-stage regulators and are more popular.

The *two-stage regulator* makes the reduction of pressure in two steps. The first step reduces the cylinder pressure to an intermediate pressure. The second step reduces this intermediate pressure to the desired working pressure. A two-stage regulator is simply two single-stage regulators in the same case. The two-stage regulator provides more accurate regulation and eliminates the need to readjust the regulator as the pressure in the supply tank is reduced. Regulators have two pressure gauges; one shows the pressure of the gas inside the cylinder; the other shows the working pressure that is being supplied to the torch. Figure 7-8 shows a cutaway view of a gas regulator.

The operation of a regulator for controlling gas pressure and providing for uniform gas flow is rather straightforward. The regulator consists of a flexible diaphragm, which controls a needle valve between the high pressure zone and the working pressure zone, a compression spring and an adjusting screw, which compensates for the pressure of the gas against the diaphragm. The needle valve is on the side of the diaphragm exposed to high gas pressure while the compression spring and adjusting screw are on the opposite side in a zone vented to the atmosphere. The spring is compressed by the adjusting knob on the outside of the regulator. In the closed position the diaphragm is flat and the needle valve closes the orifice to the high pressure zone. In this condition the compression spring is not loaded and the adjusting knob is backed off. As the knob is turned clockwise it compresses the spring, which in turn presses against the diaphragm to open the needle valve

FIGURE 7-8 Cutaway view of gas regulator.

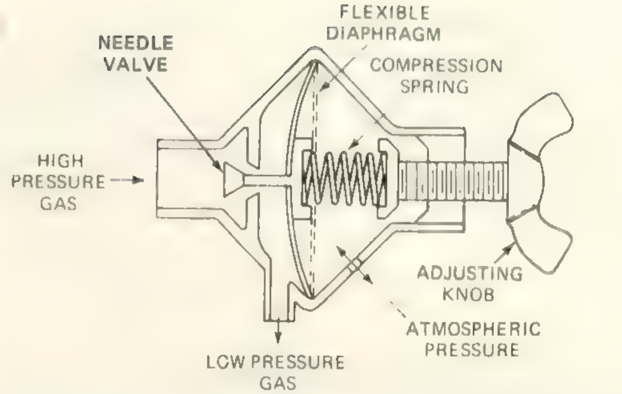


FIGURE 7-9 Gas regulator operation.

into the high-pressure zone. As the valve opens high-pressure gas enters the chamber and tends to push the diaphragm against the compression spring. This will tend to close the needle valve. When the spring is further compressed it will open the needle valve further, allowing more gas through the orifice and into the pressure zone. By balancing the compression spring against the pressure of the gas, the needle valve is kept at the right opening to allow the correct flow of gas through the orifice. The compression spring balanced against the gas pressure keeps the valve at the proper opening to allow the required flow and pressure on the low-pressure side of the regulator. Figure 7-9 shows a diagram of a gas regulator. Single-stage regulators are used for plant piping systems since the pressure in the pipe system is much lower than in the cylinder. Torches, regulators, and other gas apparatuses must be approved by one of the approving agencies. They must also be properly handled and maintained.

Gas hose, used between pieces of apparatus, is specified by its inside diameter. The ¼ in. (6.4 mm) size is the most common. The hoses may be separate or may be molded together for ease in handling. The hose fittings have the same threaded connections as the connections on the torch and the regulator (i.e., oxygen has right-hand threads and acetylene or fuel gas has left-hand threads). In addition, the acetylene hose connection has a groove around the outside to distinguish it from the oxygen hose connection. There is no common color code for gas hoses; however, in North America green is used for oxygen hose. In Europe, blue is used for oxygen hose. In North America, red is used for acetylene or fuel gas hose; however, in Europe orange is used. Black is sometimes used for oxygen hose. Hose should never be used for one gas if it was previously used for the other. The hose should be kept in good repair and if leaks occur they must be repaired or the hose replaced.

A torch must be lighted by a spark lighter consisting of a flint on a lever so it can be moved across a piece

of roughened steel. Matches or cigarette lighters or similar items should not be used to light an oxyacetylene torch since it brings the hand too close to the flame. A convenient accessory is a gas saver or economizer, which includes a bracket for hanging the torch. When the torch is hung on the bracket it closes the valves to stop the flow of oxygen and acetylene. The device has a pilot light so that when the torch is lifted from the bracket near the pilot light the torch can be lighted. This apparatus is shown in Figure 7-10.

FIGURE 7-10 Gas valve and pilot light.

Gas Supply

The oxygen required for oxyacetylene welding can be supplied in several ways. The more common way is the use of high-pressure oxygen cylinders at the welding station. Another way is to manifold oxygen cylinders and run the oxygen through a piping system to the welding stations. This is common where there are a large number of welding or cutting stations that use oxygen. When a piping distribution system is used it can be supplied by liquid oxygen if a large amount of oxygen is used.

Acetylene or fuel gases are often supplied in cylinders taken to the welding station. However, they can be piped throughout the plant in the same manner as oxygen. The acetylene may be supplied to the piping system by manifolding cylinders or by an acetylene generator. The acetylene generator produces acetylene at the plant site by the reaction of carbide and water. In all cases, the installation and operation of piping systems must be in accordance with strict specifications and safety requirements.

Filler Materials

The American Welding Society provides a specification[1] covering the composition of filler metal used with the oxyacetylene or oxyfuel gas welding process. There are three grades, RG 45, RG 60, and RG 65, having a minimum tensile stength of 45,000 psi (310 MPa), 60,000 psi (414 MPa), and 67,000 psi (462 MPa), respectively. There are no chemical composition requirements. Figure 7-2 shows the base metals weldable by the oxyacetylene welding process. This table also shows the type of filler metal required, the flame type, and the type of flux.

Welding flux is required to maintain cleanliness of the base metal, at the welding area, and to help remove the oxide film on the surface of the metal. The welding area should be cleaned. Flux melts at about the melting point of the base metal and helps protect the molten metal from the atmosphere. The molten flux combines with base metal oxides and removes them. There is no national standard for gas welding fluxes. They are categorized according to the basic ingredient in the flux or the base metal for which they are to be used. Fluxes are usually in powder form. These fluxes are often applied by sticking the hot filler metal rod in the flux. Sufficient flux will adhere to the rod to provide proper fluxing action as the filler rod is melted in the flame. Other types of fluxes are of a paste consistency which are usually painted on the filler rod or on the work to be welded. Welding rods with a covering of flux are also available. Fluxes are available from welding supply companies and should be used in accordance with the directions accompanying them.

Quality of Welds

The quality of a weld made with the oxyacetylene process can equal the quality of the base metal being welded. This is based on the use of the proper filler metal, the proper flux and the skill of the welder. The procedure will show the proper tip size, torch adjustment for the proper type of flame, and the travel speed. Figure 7-11 shows a good weld and common welding mistakes.

Welding Schedules

The oxyacetylene welding process is rarely used for joining heavy thicknesses. Figure 7-12 is a schedule that can be used for welding material ranging from the thinnest up to the heaviest. The tip size is given by showing the orifice size and the equivalent drill size, since manufacturers utilize different numbering systems for their tips. Each manufacturer relates tip size number to either the drill size or the orifice size. The length of the inner cone is shown, as well as the recommended oxygen and acetylene pressure. The diameter of the filler rod is also shown. This schedule can be used for all-position welding. The major requirement for out-of-position welding is the

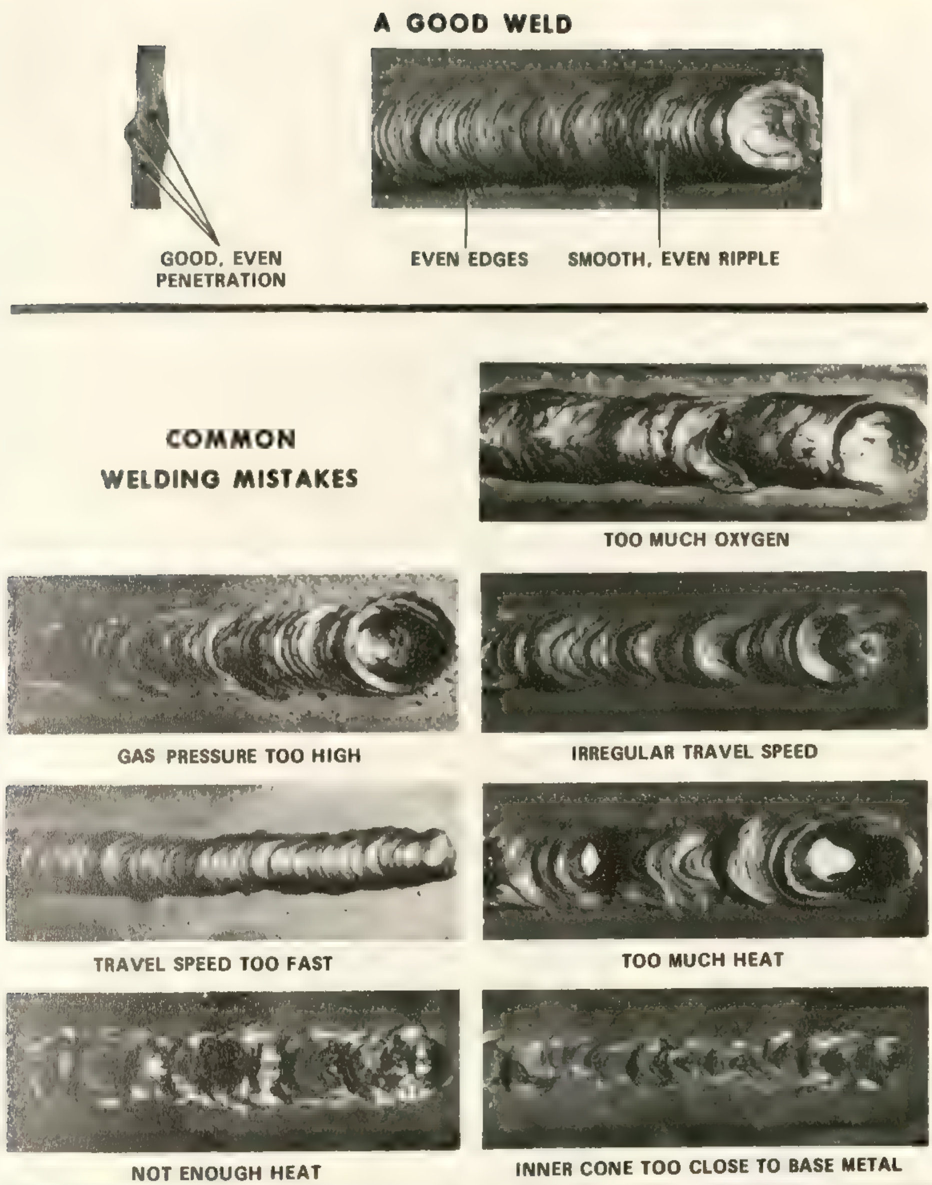


FIGURE 7-11 Quality of oxyacetylene welds.

FIGURE 7-12 Schedule of oxyacetylene welding of mild steel.

Material Thickness (Range in in.)	Filler Rod Diameter (in.)	Tip Orifice Size Drill Size	Tip Orifice Size (in.)	Cone Length of Flame (in.)	Approx. Press. of Gas: Acetylene psi	Approx. Press. of Gas: Oxygen psi	Approx. Gas Consumption: Acetylene cu ft/hr	Approx. Gas Consumption: Oxygen cu ft/hr
22-16 ga	1/16	69	0.029	3/16	1	1	2	2
1/16-1/8	3/32	64	0.036	1/4	2	2	4	4
1/8-3/16	1/8	57	0.043	5/16	3	3	10	10
3/16-5/16	1/8	55	0.052	3/8	4	4	20	20
5/16-7/16	5/32	52	0.064	7/16	5	5	45	45
7/16-1/2	3/16	49	0.073	1/2	6	6	60	60
1/2-3/4	3/16	45	0.082	1/2	7	7	70	70
3/4-1	1/4	42	0.094	9/16	8	8	80	80
over 1 inch	1/4	36	0.107	5/8	9	9	90	90
Heavy Duty	1/4	28	0.140	3/4	10	10	100	100

Note: Based on use of neutral flame. For welding clean steel flux is not normally used. There is no standardized tip size for gas torches —thus table gives data based on tip orifice size in drill size and inch diameter. There are no metric equivalents.

control of the weld puddle, which relates to the skill of the welder.

This schedule is based on welding of clean mild steel using a neutral flame and not using a flux. Information concerning the welding of the different metals is provided in the metals chapters.

Safety Considerations

The oxyacetylene process is a safe welding process, provided that proper precautions are taken. Normal precautions involve the respect for open flames, for compressed gases, for combustible gases, and for hot metal. Eye and skin protection is different since the flame is not nearly as bright as an arc. Goggles with the appropriate colored lenses are used and headshields are normally not required. Installation of the equipment and apparatus is extremely important and if piping and manifold systems are used, they must be installed with strict compliance to codes. Torches should always be properly stored when not in use. Hoses and torches should be bled so that gas pressure does not remain in the torch or hoses. Oil or grease should never be used on gas apparatus. Review Chapter 3 for complete information.

Limitations of the Process

The equipment for oxyacetylene welding is the least expensive of all. It is one of the slowest processes due to the heat transfer and temperature involved. For this reason oxyacetylene welding has been largely supplanted for most manufacturing operations. The most popular uses for oxyacetlene are torch brazing and oxygen flame cutting.

Variations of the Process

The main variation is gas pressure welding. In this process the entire area of abutting surfaces is heated with gas flames. When the heating is completed the flames are removed and pressure is applied to achieve the weld. This process has been used for joining tubular members such as pipe. It has also been used for joining railroad rails and other parts. It is not of major industrial significance today.

The other variation is the use of hydrogen instead of acetylene. If hydrogen is used the apparatus must be proper for hydrogen and equipment designed for acetylene cannot be used. Oxyhydrogen welding is not too popular and for this reason additional details are not presented.

7-2 BRAZING

Brazing (B) is a group of welding processes that produce coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having a liquidus above 840 °F (450 °C) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action.

The *solidus* is the highest temperature at which a metal or an alloy is completely solid, that is, the temperature at which melting starts. The *liquidus* is the lowest temperature at which a metal or an alloy is completely liquid, that is, the temperature at which freezing starts. The solidus and liquidus for a particular metal or alloy are definite.

There are many different ways of brazing, and they all pertain to the method of applying heat.

Dip Brazing

There are two methods of dip brazing (DBR), (1) molten chemical bath dip brazing and (2) molten metal bath dip brazing. In both cases brazing is accomplished by immersing clean and assembled parts into a molten bath. Dip brazing is used for brazing small parts. The assembly should be self-jigging so the parts will maintain the proper relationship until the brazing filler metal has completely solidified. By using a high-quality furnace and controller, close temperature control is obtained with the dip brazing method.

The molten material is contained in a pot type furnace, which is heated by oil, gas, or electricity, or by means of electrical resistance units placed in the bath. Normally, the parts to be brazed are first preheated in an air-circulating furnace. When the parts have reached the preheat temperature, they are immersed in the molten bath.

The difference between the two methods of dip brazing is the molten material in the pot. In the molten chemical bath, the bath is called a flux bath. When a chemical bath is used the filler metal must be preplaced in the joints that are to be brazed. Fluxing of the assembly is not required.

The other method of dip brazing utilizes molten metal. The molten brazing material will flow into the joints to be brazed by capillary attraction. The parts must be clean and fluxed prior to dip brazing. A flux cover should be maintained over the surface of the molten metal bath.

Dip brazed parts normally distort less than torch brazed parts because of the uniform heating. It is suited for moderate- to high-production runs because the tooling is relatively complex. The method of applying the process may be manual or automatic. The process is suited for brazing small to medium parts with multiple or hidden joints. It can be used for all the metals that can be brazed and is particularly suited for aluminum and other alloys that have melting points very close to the brazing temperature. The brazing operation can also perform certain of the heat treating operations on aluminum.

Furnace Brazing

Furnace brazing (FBR) is accomplished by placing cleaned parts in a furnace. The parts should be self-jigging and assembled, with filler materials preplaced near or in the joint. The preplaced brazing filler material may be in the form of wire, foil, filings, slugs, powder, paste, tape, and so on. The furnaces are usually heated by electrical resistance. Other types of fuel can be used but only for muffle-type furnaces. Automatic temperature controllers are required so that they can be programmed for the brazing temperatures and for cooling. The batch-type furnace is used for medium-production work. A continuous-conveyor-type furnace is used for high-volume work. When continuous furnaces are used, several temperature zones may be employed, which provide the proper preheat, brazing, and cooling temperature. In either type, specialized holding fixtures are required.

Flux is employed except when an atmosphere is specifically introduced in the furnace to perform this function. Flux should not be used where postbraze cleaning is made difficult by the complexity of the design of the brazed parts. Furnace brazing is often done without the use of flux but by the use of special atmospheres in the brazing furnace. Flux is not necessary if the brazing is done in a reducing-gas atmosphere, such as hydrogen or other special gases. Inert gases—argon or helium—are sometimes employed to obtain special properties. Furnace brazing can also be performed in a vacuum which prevents oxidation and may eliminate the need for flux. Vacuum brazing is widely used in the aerospace and nuclear fields where reactive metals are being joined and where entrapped fluxes would not be acceptable. In vacuum brazing, the vacuum is maintained by continuous pumping which will remove volatile constituents liberated during the brazing operation. There are some base metals and filler metals which cannot be brazed in a vacuum since low-boiling-point or high-vapor-pressure constituents would be volatized and lost. The vacuum is a relatively economical method and is an accurately controlled atmosphere. It provides for surface cleanliness and allows the flow of filler metals without the use of fluxes.

It is important to select the correct atmosphere based on the type of base metals and filler metals being employed. For example, copper brazing of steels is normally done in a reducing atmosphere of high-purity hydrogen.

The distortion of furnace brazed assemblies is less than torch brazed parts. Furnace brazing is suitable for joining thin sections to thick sections. It can be used for brazing parts of all sizes having multiple joints and hidden joints. Most metals are completely annealed as a result of furnace brazing. In some cases the heat treating operation can be done in conjunction with the brazing cycle, provided that the two programs are compatible.

Induction Brazing

The heat for induction brazing (IBR) is obtained from the resistance of the work to an electrical current induced in the parts to be brazed. The parts or joint are placed in an alternating-current field but do not become a part of the electrical circuit. High-cycle alternating current ranging from 5000 to 5,000,000 Hz can be used. In general, motor generator alternating current sources operate in the range 5000 to 10,000 Hz, spark gap oscillator units operate in the range 20,000 to 300,000 Hz, and solid-state oscillator units operate in the range 200,000 to 5,000,000 Hz. The output is fed into a copper tubing work coil, usually water cooled, designed specifically to fit the shape of the parts to be brazed. They do not touch the parts but are coupled to them by the electrical field. The design of work coils and how they are coupled to the workpieces is quite complex. For more infomation, see Ref. 2. The frequency of the power source determines the type of heat that will be induced in the part. High-frequency power sources produce skin heating in the parts. Lower-frequency current results in deeper heating and is used for brazing heavier sections. Heating of the part usually occurs within 10 to 60 seconds. Sufficient time must be provided for the filler metal to flow through the entire joint and to form good fillets at the interface.

Induction brazing is ideally suited for high-volume manufactured parts. Mechanized systems for moving the parts to and from the coil are quite common. The filler metal is normally preplaced in the joint and the brazing operation can be done in air, in an inert-gas atmosphere, or in a vacuum. Brazing fluxes may or may not be used, depending on whether the work is done in the vacuum, in air, or in inert gas. The major advantage of induction brazing is the rapid heating rates that make it suitable for brazing with filler metal alloys that tend to vaporize or segregate. A disadvantage of induction brazing is that the heat may not be uniform. Thin sections tend to heat up quicker than heavy sections and thin sections may tend to overheat. Field or shading coils are sometimes used to reduce the problem of overheating. Induction brazing is applied as an automatic process.

Infrared Brazing

In infrared brazing (IRBR) the heat is obtained from infrared heat or a *black* heat source below the red rays in the spectrum. There is some visible light involved but the principal heating is done by the invisible radiation. Heat sources or lamps capable of delivering up to 5000 W of radiant energy are used. The lamps do not necessarily need to follow the contour of the parts being brazed even though the heat input varies by the square of the distance from the source. Radiation concentrating reflectors are often used. Sources other than electric lamps, but supplying infrared radiation, can be used. Parts to be brazed

are positioned so that the radiant energy will impinge on the joint.

With infrared brazing, as in furnace brazing and induction brazing, the parts can be contained in air, in an inert atmosphere, or in a vacuum. The same comments concerning fluxes and atmospheres apply. Infrared brazing is not as fast as induction brazing; however, the equipment required to provide the heat is much less expensive. Infrared brazing is designed for automatic application and is not applied manually. Normally, the parts to be brazed are self-jigging and the filler material is preplaced in or near the joint.

Resistance Brazing

In resistance brazing (RBR) the heat is obtained from the resistance to the flow of an electrical current through the parts being brazed. The parts become a part of the electrical circuit. Electrodes may be copper alloys or carbon-graphite material. Resistance-welding machines can be used for supplying the electric current to the parts. When resistance-welding equipment is used it is used at a lower power input than when it is used for resistance welding. Specially designed machines for resistance brazing are also used. Alternating current is normally employed. Direct current may be used but is not as common. The parts to be brazed are held between the two electrodes while the correct pressure and electrical current are applied. The pressure is maintained until the filler metal has solidified. High-amperage current at low voltage is used. The heat is generated at the brazed joint interface and at the electrode to the part interface and depends on the resistance to the current flow at these locations.

Resistance brazing is normally limited to applications where the brazing filler metal is preplaced; however, face feeding of the filler metal into the joint may be used. Resistance brazing is normally used for low-volume production where heating is localized at the area to be brazed.

The flux used for resistance brazing must be given specific attention since the conductivity of the flux is important. Normally, brazing fluxes are insulators when cool and dry. When they become molten from the heat of the brazing operation, they may become conductive. Fluxes are normally employed except when an atmosphere is utilized to perform the same function.

Torch Brazing

Torch brazing (TBR) is done by heating the parts to be brazed with the flame of a gas torch or torches. The temperature and the amount of heat required determine the gases used. The flame can be supplied by acetylene, or other fuel gas which may be burned with air, compressed air, or oxygen. For manual torch brazing, normally a single torch and tip are used, but for automatic torch brazing multiple tips may be required. Manual torch brazing is probably the most widely used brazing method and is shown in Figure 7-13. Torch brazing is very useful on assemblies that involve heating sections of different mass. The flame can be directed to the heavier part to produce uniform heating. Manual brazing is particularly useful for repair work. Automatic torch brazing is used in manufacturing operations where the rate and volume of production warrants the expense. An automatic brazing operation for an electrical part is shown in Figure 7-14. Normally, the work will move under or between multiple torches, as shown in this application.

FIGURE 7-13 Torch brazing manually applied.

For torch brazing the atmosphere is the product of the combustion of the flame. The neutral or reducing flame is normally used. A slightly oxidizing flame may be used for certain materials. The brazing filler metal may be preplaced in or at the joint, or it may be face fed manually.

The parts must be assembled and self-jigging or held in place by mechanical means during the heating and cooling cycle. The parts must be cleaned, and flux is added to assist the capillary flow of the filler material. Position is not too important; however, gravity can be helpful in assisting capillary flow in complex joints.

Torch brazing can be used for a variety of materials. It can be used when parts of unequal mass are being brazed; however, because of the poor temperature control, metals that have a melting point close to the brazing temperature are not normally torch brazed. Torch-brazed parts tend to have warpage or distortion when joining parts of different thicknesses. Torch brazing is

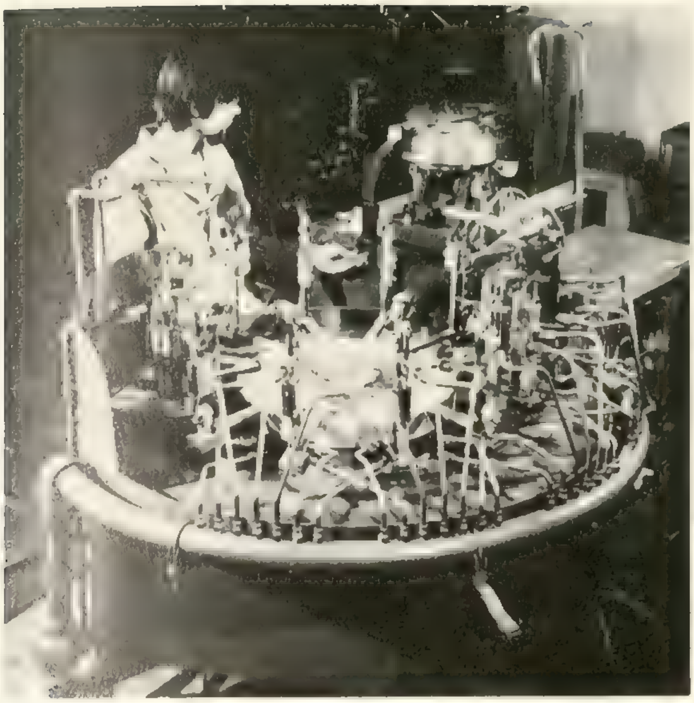


FIGURE 7-14 Automatic torch brazing electrical parts.

used when the part to be brazed is too large, is an unusual shape, or cannot be heated by the other methods.

Other Brazing Methods

Other methods of brazing involve different methods of supplying the heat. Exothermic brazing, which utilizes the heat of specific chemical reactions, can be used. An exothermic chemical reaction is any reaction between two or more chemicals in which heat is given off due to the free energy of the reaction. The solid-state or nearly solid-state metal oxide reactions are used. This method is not employed widely.

Other sources of heat can be any of the arc processes, where the arc is used as a source of heat. This includes the carbon arc, the twin-carbon arc, the gas tungsten arc, and the plasma arc processes. The laser beam and the electron beam can also be used. The heat input–heat loss relationship must be carefully controlled to avoid melting the parts to be brazed.

Almost all of the common metals can be brazed. The different metals and their **brazability**—that is, the capacity of a metal to be brazed under the fabrication conditions are listed in Figure 7-15.

The thicknesses of the parts to be joined are dependent on the ability of providing sufficient heat to the heavier sections without excessive heat to the thinner sections. This can be a problem with some of the brazing methods and is a major consideration in selecting the heating method.

Filler Materials and Fluxing

Filler materials for brazing are covered by an AWS specification.[2] They are classified according to analysis: aluminum–silicon, copper, copper–zinc, copper–phosphorus, nickel–gold, heat-resisting materials, magnesium, and silver are the basic groupings. The composition of the different filler metals, as well as the operating range and recommended uses, are given by Figure 7-16. Filler metal selection is based on the metal being brazed.

Certain brazing filler metals contain cadmium in significant amounts. When these are used adequate ven-

Base Metal	Filler Metal Type	Torch Brazing Flame Type	AWS Flux Type
Aluminums	Alum-silicon	Slightly reducing	Flux No. 1
Brasses	Silver alloy	Slightly reducing	No. 3A or 3B
Bronzes	Copper zinc	Slightly reducing	Flux No. 3B
Copper	Copper zinc	Slightly reducing	Flux No. 3B
Inconel	Silver alloy	Slightly reducing	No. 3A or 3B
Iron, cast, nodular	Silver alloy	Neu/slight oxid.	No. 3A or 3B
Iron, wrought	Copper zinc	Slightly reducing	Flux No. 3B
Monel	Silver alloy	Slightly reducing	No. 3A & 3B
Nickel	Silver alloy	Slightly reducing	No. 3A & 3B
Nickel copper	Copper	Slightly reducing	No. 3B
Nickel silver	Silver alloy	Slightly reducing	No. 3A or 3B
Precious metals	Variable	Variable	Variable
Steel low alloys	Copper zinc	Slightly reducing	No. 3B
Steel high carbon	Copper zinc	Slightly reducing	No. 3B
Steel low carbon	Copper zinc	Slightly reducing	No. 3B
Steel medium carbon	Copper zinc	Slightly reducing	No. 3B
Stainless steel	Silver alloy	Sigtly reduc/neu.	No. 4

Note: In many cases, different filler metals may be used. The easiest to use filler metal is shown above. Color matching has been ignored.

FIGURE 7-15 Brazeability of base metals using torch brazing.

AWS Classification	Brazing Temperature Range F°	C°	Nominal Composition (%)
Aluminum-silicon alloys			
BAlSi-2	1110-1150	599-621	92.5 Al, 7.5 Si
BAlSi-3	1060-1120	571-601	86 Al, 10 Si, 4 Cu
BAlSi-4	1080-1120	582-604	88 Al, 12 Si
BAlSi-5	1090-1120	588-604	90 Al, 10 Si
Magnesium alloys			
BMg-1	1120-1160	604-627	89 Mg, 2 Zn, 9 Al
BMg-2a	1080-1130	582-610	83 Mg, 5 Zn, 12 Al
Copper-phosphorus alloys			
BCuP-1	1450-1700	788-927	95 Cu, 5P
BCuP-2	1350-1550	732-843	93 Cu, 7 P
BCuP-3	1300-1500	704-816	89 Cu, 5 Ag, 6 P
BCuP-4	1300-1450	704-788	87 Cu, 6 Ag, 7 P
BCuP-5	1300-1500	704-816	80 Cu, 15 Ag, 5 P
Copper-copper zinc alloys			
BCu-1	2000-2100	1093-1149	99.9 Cu (min)
BCu-1a	2000-2100	1093-1149	99.0 Cu (min)
BCu-2	2000-2100	1093-1149	86.5 Cu (min)
RBCuZn-A	1670-1750	910-954	57 Cu, 42 Zn, 1 Sn
RBCuZn-D	1720-1800	938-982	47 Cu, 11 Ni, 42 Zn
Silver alloys			
BAg-1	1145-1400	618-760	45 Ag, 15 Cu, 16 Zn, 24 Cd
BAg-1a	1175-1400	635-760	45 Ag, 15 Cu, 16 Zn 24 Cd
BAg-2	1295-1550	700-843	45 Ag, 26 Cu, 21 Zn, 18 Cd
BAg-2A	1310-1550	710-843	30 Ag, 27 Cu. 23 Zn, 20 Cd
BAg-3	1270-1500	688-816	52 Ag, 15 Cu, 15 Zn, 15 Cd, 3 Ni
BAg-4	1435-1650	780-899	40 Ag, 30 Cu, 23 Zn, 2 Ni
BAg-5	1370-1550	743-843	45 Ag, 30 Cu, 25 Zn
BAg-6	1425-1600	774-871	53 Ag, 31 Cu, 16 Zn
BAg-7	1205-1400	651-760	56 Ag, 22 Cu, 17 Zn, 5 Sn
BAg-8	1435-1650	780-899	77 Ag, 23 Cu
BAg-8a	1410-1600	766-871	77 Ag, 23 Cu
BAg-13	1575-1775	857-635	54 Ag, 40 Cu, 5 Zn, 1 Ni
BAg-13a	1600-1800	871-982	56 Ag, 42 Cu, 2 Ni
BAg-18	1325-1550	718-843	60 Ag, 40 Cu
BAg-19	1610-1800	877-982	92 Ag, 8 Cu
Precious metals			
BAu-1	1860-2000	1016-1093	37 Au, 63 Cu
BAu-2	1635-1850	890-1010	79.5 Au, 20.5 Cu
BAu-3	1885-1995	1030-1090	34 Au, 62 Cu, 4 Ni
BAu-4	1740-1840	949-1004	82 Au, 18 Ni
Nickel alloys			
BNi-1	1950-2200	1066-1204	14 Cr, 3 Br, 4 Si, 4 Fe, 75 Ni
BNi-2	1850-2150	1010-1177	7 Cr, 3 Br, 4 Si, 3 Fe, 83 Ni
BNi-3	1850-2150	1010-1177	3 Br, 4 Si, 2 Fe, 91 Ni
BNi-4	1850-2150	1010-1177	1 Br, 3 Si, 2 Fe, 94 Ni
BNi-5	2100-2200	1149-1204	19 Cr, 10 Si, 71 Ni
BNi-6	1700-1875	927-1025	11 Br, 89 Ni
BNi-7	1700-1900	927-1038	13 Cr, 10 Br, 77 Ni

FIGURE 7-16 AWS filler metals for brazing.

tilation is required. Filler metals are available in many forms; the most common is the wire or rod. Filler metal is also available as thin sheet, powder, paste, or as a clad surface of the part to be brazed.

The placement of the filler metal affects the quality of the joint. For normal lap joints the filler metal should be supplied at only one end and allowed to flow completely through the joint by capillary action. If the filler metal is supplied at both ends gas will be trapped in the joint and will create voids which will drastically reduce the effective area of the braze. Another advantage of supplying filler metal at only one end is for quality control. It will be apparent that the brazed joint is complete if the filler material creates a fillet at the end. Filler metal cannot be made to flow by means of capillary action into a blind joint. Gas will be trapped and will not allow complete flow of filler metal throughout the faying surfaces. In such cases venting must be provided. This

applies also to small tanks or vessels. The gas in these containers will expand as a result of the heat and will prevent filler metals from penetrating the abutting surfaces.

The correct fluxing material must be used. The American Welding Society has established fourteen different types of fluxes which satisfy most brazing requirements.[3] Figure 7-17 shows the fluxes, as well as the recommended use and types of filler metals and temperature range that they are designed to meet.

Some brazing fluxes contain fluorine compounds. The package will show a precautionary label stating that adequate ventilation is required. The ventilation requirement must be followed. The AWS Brazing Manual provides specific information.[4]

The placement of the flux also affects the quality of the brazed joint. Paste flux is the most common form and is usually spread over the surfaces to be joined. It is also painted on the preplaced brazing filler materials. Brazing fluxes can be sprayed for high-volume production. In addition, liquid flux can be introduced into the fuel gas and supplied to the flame for torch brazing at the point where it is needed. Flux in the flame may not be satisfactory for large, deep, or complex joints. In such cases preplaced paste flux may also be required.

Joint Designs

When designing a joint for brazing, the following six factors must be considered:

1. The type of joint required
2. The clearance between the parts
3. The surface finish of the faying surfaces
4. Placement of the filler metal
5. The placement of the flux when used
6. The possibility of gas entrapment

Brazed joints fall into two general types, *butt joints* and *lap joints*. Butt joints are subjected to tensile or compressive loads and lap joints are normally subjected to shear loading. There are many variations of these two types. Butt joints provide a limited area for brazing. The strength of the filler material is usually less than the

FIGURE 7-17 Fluxes for brazing. (From Ref. 12.)

AWS Brazing Flux Type No.	Base Metals Being Brazed	Recommended Filler Metals	Recommended Useful Temp. Range F°	C°	Major Flux Ingredients	Forms Available
1	All brazeable aluminum alloys	BAISi	700–1190	371–643	Chlorides Fluorides	Powder
2	All brazeable magnesium alloys	BMg	900–1200	482–649	Chlorides Fluorides	Powder
3A	Copper and copper-base alloys (except those with aluminum) iron-base alloys; cast iron; carbon and alloy steel; nickel and nickelbase alloys; stainless steels; precious metals	BCuP BAg	1050–1600	566–871	Boric acid Borates Fluorides Fluoborates Wetting Agent	Powder Paste Liquid
3B	Copper and copper-base allows (except those with aluminum); iron-base alloys; cast iron; carbon and alloy steel; nickel and nickel-base alloys; stainless steel; precious metals	BCu BCuP BAg BAu RBCu Zn BNi	1350–2100	732–1149	Boric acid Borates Fluorides Fluoborates Wetting Agent	Powder Paste Liquid
4	Aluminum bronze, aluminum brass and iron or nickel-base alloys containing minor amounts of Al and/or Ti	BAg (all) BCuP (copper-base alloys only)	1050–1600	566–871	Chlorides Fluorides Borates Wetting Agent	Powder Paste
5	Same as 3A and B above	Same as 3B excluding BAg through −7)	1400–2200	760–1204	Borax Boric acid Borates Wetting Agent	Powder Paste Liquid

strength of the base metal. A butt joint will not provide 100% joint efficiency. If the joint is scarfed to form a bevel, additional area will be provided which will increase the strength of the brazed joint. The bevel area should provide at least three times the area that is obtained with a simple square butt joint. This joint detail is shown in Figure 7-18. Unfortunately, scarf joints are more difficult to hold in alignment than the square butt or lap joints.

Lap joints are more widely used since they can be designed to provide sufficient brazed area so that the joint is as strong as the base metal. Unfortunately, lap joints tend to be unbalanced joints and this produces stress concentrations which adversely affect the joint strength. Every effort should be made to provide a balanced lap joint to properly carry the load. Figure 7-18 shows the different brazed joints and the recommended types.

The clearance between the parts being joined is important. If the joint clearance is too small it will not allow capillary attraction to cause the filler metal to flow uniformly throughout the entire joint. If the clearance is too great, filler metal may not flow throughout the joint, and a low strength joint will result. The brazing filler metal also has an influence on the clearance. Another factor is the length or area of the joint. For smaller areas, a smaller joint clearance can be used. In general, when using an atmosphere system smaller joint clearances can be used. Where fluxes are required the clearances are normally larger. Clearances range from 0.001 to 0.025 in. (0.025 to 0.635 mm) for clearance when fluxes are involved. The recommended clearances of different groups of brazing filler metals are shown in Figure 7-19.

It is important to compensate for unequal expansion and contraction of a joint design. This can occur when brazing dissimilar metals and when the difference of thermal expansion would create tensile loads on the filler metal during cooling.

The surface finish of the faying surfaces should be between 30 and 80 microinches for best joint strength. The filler metal may not wet the surfaces completely if they are too smooth. Furthermore, the filler metal will

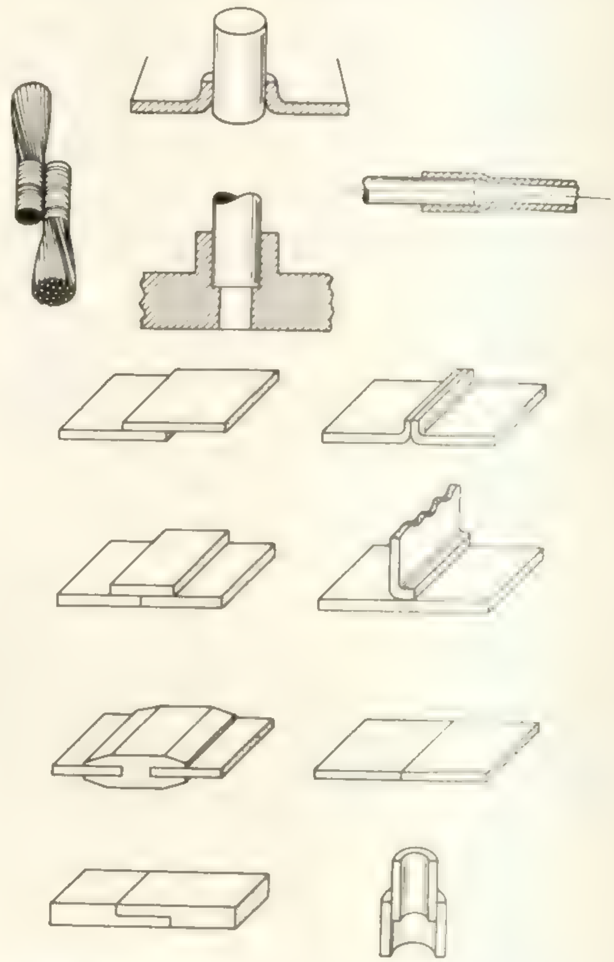


FIGURE 7-18 Joint details for brazing.

FIGURE 7-19 Recommended joint clearance of brazing temperature.

Filler Metal AWS Classification	Joint Clearance in.	mm	Brazing Conditions
BAlSi group	0.002-0.008	0.051-0.203	For length of lap less than 1/4" (6.4mm)
	0.008-0.010	0.203-0.254	For length of lap greater than 1/4" (6.4mm)
BCuP group	0.001-0.005	0.025-0.127	No flux or mineral brazing fluxes
BAg group	0.002-0.005	0.051-0.127	Mineral brazing fluxes
	0.000-0.002	0.000-0.051	Gas atmosphere brazing fluxes
BAu group	0.002-0.005	0.051-0.127	Mineral brazing fluxes
	0.000-0.002	0.000-0.051	Gas atmosphere brazing fluxes
BCu group	0.000-0.002	0.000-0.051	Gas atmosphere brazing fluxes
BCuZn group	0.002-0.005	0.051-0.127	Mineral brazing fluxes
BMg	0.004-0.010	0.102-0.254	Mineral brazing fluxes
BNi group	0.002-0.005	0.051-0.127	General applications flux or atmosphere
	0.000-0.002	0.000-0.051	Free flowing types, atmosphere brazing

not distribute itself throughout the complete joint by capillary attraction if they are too smooth. If the surfaces are too rough, only the high points may be properly brazed. With very rough surfaces the clearance will be too great to provide optimum strength of the brazed joint.

Joint Cleanliness

It is important to have extremely clean surfaces for the brazed joint. Mechanical surface preparations such as grinding, sand blasting, wire brushing, filing, and machining can be used. However, in every case care must be taken to make sure that the surface is clean. For example, grit should not become embedded in the surface. Wire brushing can result in the folding in of oxides and burnishing of the surface. Chemical cleaning can be used to remove dirt and oils. Solvents, alkaline baths, acid baths, salt bath pickling, and ultrasonic cleaning have all been used successfully. When the surfaces have been cleaned, flux is used to protect the surface from oxidation or from other undesirable chemical action during the heating and brazing operation. Fluxes are not designed to clean joints. They are designed to keep cleaned joints clean during the brazing operation. They will combine with, dissolve, or inhibit the formation of chemical compounds which might interfere with the quality of the brazed joint.

Braze Quality

Close adherence to the design factors, filler metal selection, flux selection, and cleanliness will insure quality brazed joints. When the joint does not exhibit the quality required, investigate using the following troubleshooting hints:

1. The brazing filler metal does not wet the surface and balls up instead of flowing into the joint.
   (a) Increase the amount of flux used.
   (b) Roughen the surface slightly, especially the surface of cold-drawn or cold-rolled stock.
   (c) Acid pickle parts to remove surface oxides.
   (d) Change work position so that gravity will help the filler metal fill the joint.
2. The brazing alloy does not flow through the joint even though it melts and forms a fillet.
   (a) Allow more time for heating.
   (b) Heat to a higher temperature.
   (c) Determine the clearance in the joint and if required rework it to be looser or tighter.
   (d) Apply flux to both the base metals and brazing filler metal.
   (e) Do a more thorough cleaning job before assembly.
3. The assembled joint was tight and it opens up during brazing.
   (a) The clearance was too small and a load was introduced into one part which causes the opening.
   (b) The parts have unequal coefficients of expansion due to dissimilar metals.
   (c) Unsupported section might cause improper clearances due to sag from heating.
4. The brazing filler metal melts but does not flow.
   (a) Coat the filler metal with flux before using and apply flux generously to the base metal.
   (b) Mechanically or chemically clean the filler metal if there are surface oxides present.
5. The brazing filler metal flows away from the joint instead of into the joint.
   (a) Provide a reservoir in the joint into which the brazed filler metal can flow.
   (b) Reposition the assembly so that gravity will help the filler metal flow into the joint.
   (c) Remove burrs, edges, or other obstacles over which the brazing alloy might not flow.

Above all, make sure that the filler metal alloy is compatible with the base metal and that the proper temperatures and fluxes are employed.

To determine the strength of a brazed joint the standard method should be used.[5] The AWS Standard outlines the procedure to be used for making tests that are comparable to others.

For certain work the brazer, or one who performs a manual or semiautomatic brazing operation, must be qualified. Qualification is in accordance with Section IX, of the "ASME Boiler and Pressure Vessel Code."[6] Part C pertains to brazing ferrous and nonferrous materials. This specification must be read carefully. It introduces new uses for positions in flat flow, vertical down flow, vertical up flow, horizontal flow, and special positions.

Disadvantages and Uses

There are several disadvantages to brazing. There is the possibility of lack of *color match* of the parts being brazed and the brazing filler material. The strength of brazed joints may be less than the strength of the parts being joined.

Brazing is widely used throughout industry, and applications are so numerous that it is impossible to list them. Three major industries using brazing are the electrical industry, the utensil-manufacturing industry, and the maintenance and repair industry.

7-3 SOLDERING

Soldering (S) is a group of welding processes that produce coalescence of material by heating them to the soldering temperature and by using a filler metal having a liquidus not exceeding 840 °F (450 °C) and below the

solidus of the base metals. The filler metal is distributed between closely fitted faying surfaces of the joint by capillary action.

Solder is a filler metal used in soldering that has a liquidus not exceeding 840 °F (450 °C). The solder or the filler metal is normally a nonferrous alloy. The temperature of 840 °F (450 °C) is the temperature that differentiates soldering from brazing. This arbitrary number was selected many years ago and is universally accepted. Most of the factors involved with brazing apply to soldering. In fact, slang usage of the terms "soft solder" and "hard solder" or "silver solder" attempts to differentiate between soldering and brazing. Brazing and soldering, the two metal joining processes using filler metals that melt at temperatures below the temperature of the base metal, are much older than the arc welding processes.

There are at least eight soldering methods in wide use today. These can be classified into three general groups. One group relates to the means of applying heat and two groups are related to the means of applying the solder with or without flux.

The mechanism for joining by soldering involves three closely related factors: (1) wetting, (2) alloying, and (3) capillary attraction. Wetting is the bonding or spreading of a liquid filler metal or flux on a solid base metal. For soldering it is more specific. When molten solder leaves a continuous permanent film on the metal surface of the base metal it is said to have *wet* that surface. *Wetting* occurs when there is a stronger attraction between certain atoms of the solder and the base metal than between the atoms of the *solder*. Wetting is essentially a chemical reaction. It occurs when one or more elements of the solder react with the base metal being soldered to form a compound.

The ability of a solder to alloy with the base metal is related to its ability of wetting the surface. Heat is applied to facilitate wetting. Alloying is related to the cleanliness of the base metal. The base metal must be oxide free, and this is accomplished by cleaning and using a flux. There must be intimate contact between the solder and the base metal for alloying to occur at the interface. The temperature of wetting may not correspond with the liquidus temperature of the solder alloy. Many metals can be soldered, including aluminum, copper-base alloys, nickel-base alloys, steels, and stainless steel.

The fluidity of the molten solder must be such that it can flow into narrow spaces by capillary attraction. Tests are available to determine this quality. The fluidity of the molten solder is the property that influences the spreading of the solder over the base metal surface. The flowability or spread of solder can also be determined by tests.

The actual application of the solder involves two steps. The wetting of the base metal surface with solder and the filling of the gap between the wetted surfaces with the solder. These two steps are normally carried out together depending on conditions and application; however, for "difficult-to-solder" metals it is desirable to wet the surface of the base metal with solder prior to making the joint. This is called *tinning* or *precoating*.

Strength of Soldered Joints

The strength of a soldered joint depends on the design of the joint and its clearance. Usually, joints stressed in tension are not successful. The normal type joint is the lap joint where sufficient overlap occurs to provide enough area for required strength. The clearance between the parts being joined must be held to close limits. The maximum strength of the joint will provide a joint considerably stronger than the strength of the solder alloy. However, if clearance between the joint is excessive, the strength of the joint drops to the strength level of the soldering alloy.

Soldering Procedures

Seven factors are involved in producing a high-quality soldered joint:

1. *Design and fit of the joint.* The lap joint is the only one that has sufficient strength for most requirements. Clearance between the parts being joined should be sufficient so that the solder will be drawn into the joint by means of capillary attraction. The clearance of from 0.003 to 0.005 in. (0.07 to 0.12 mm) is recommended for most applications. The joint design is the same as used for brazing.
2. *Precleaning.* The joint area must be free of all grease, oil, dirt, oxides, and so on. This is best done by mechanical or chemical cleaning. Solder will not wet a dirty surface or a surface covered with oxides. Cleaning can be accomplished by brushing, filing, machining, sanding, and also by the use of chemicals.
3. *Selection and application of the flux.* The flux helps remove oxides but the flux must be designed so that it can be removed after the joint is soldered. It should be fluid at the same or at a lower temperature than the liquidus of the solder. It should have a lower specific gravity than the solder so that the solder will displace it in the joint. It should promote wetting of the surface by the solder. Stronger fluxes are the acid fluxes or the inorganic type. Intermediate fluxes are less severe. The organic type fluxes such as resin are the mildest and are often referred to as *pure water, white resin,* or *nonactivated resin*. Resin contains an abietic acid which is very mild, has a long melting point, and remains

effective to the highest-melting-point solder is normally used. Flux should be applied to the base metal to protect it from oxidation.

Solder is available with the flux contained in its core. The amount of flux in the core ranges from about 0.5% to over 3%, 2.2% the most common. Resin-core solder and acid-core solders are available. The resin-core type is used for electrical work, and the acid-core type is used for sheet metal work.

4. *Selection and application of the solder.* There are two specifications[7, 8] that apply to the different types of solder. Figure 7-20 shows the nominal composition of the solder, its melting range, and typical applications. The 50 A (50% lead, 50% tin) is the

AWS Classification	Brazing Temperature Range F°	C°	Nominal Composition (%)
Aluminum-silicon alloys			
BAlSi-2	1110-1150	599-621	92.5 Al, 7.5 Si
BAlSi-3	1060-1120	571-601	86 Al, 10 Si, 4 Cu
BAlSi-4	1080-1120	582-604	88 Al, 12 Si
BAlSi-5	1090-1120	588-604	90 Al, 10 Si
Magnesium alloys			
BMg-1	1120-1160	604-627	89 Mg, 2 Zn, 9 Al
BMg-2a	1080-1130	582-610	83 Mg, 5 Zn, 12 Al
Copper-phosphorus alloys			
BCuP-1	1450-1700	788-927	95 Cu, 5P
BCuP-2	1350-1550	732-843	93 Cu, 7 P
BCuP-3	1300-1500	704-816	89 Cu, 5 Ag, 6 P
BCuP-4	1300-1450	704-788	87 Cu, 6 Ag, 7 P
BCuP-5	1300-1500	704-816	80 Cu, 15 Ag, 5 P
Copper-copper zinc alloys			
BCu-1	2000-2100	1093-1149	99.9 Cu (min)
BCu-1a	2000-2100	1093-1149	99.0 Cu (min)
BCu-2	2000-2100	1093-1149	86.5 Cu (min)
RBCuZn-A	1670-1750	910-954	57 Cu, 42 Zn, 1 Sn
RBCuZn-D	1720-1800	938-982	47 Cu, 11 Ni, 42 Zn
Silver alloys			
BAg-1	1145-1400	618-760	45 Ag, 15 Cu, 16 Zn, 24 Cd
BAg-1a	1175-1400	635-760	45 Ag, 15 Cu, 16 Zn 24 Cd
BAg-2	1295-1550	700-843	45 Ag, 26 Cu, 21 Zn, 18 Cd
BAg-2A	1310-1550	710-843	30 Ag, 27 Cu. 23 Zn, 20 Cd
BAg-3	1270-1500	688-816	52 Ag, 15 Cu, 15 Zn, 15 Cd, 3 Ni
BAg-4	1435-1650	780-899	40 Ag, 30 Cu, 23 Zn, 2 Ni
BAg-5	1370-1550	743-843	45 Ag, 30 Cu, 25 Zn
BAg-6	1425-1600	774-871	53 Ag, 31 Cu, 16 Zn
BAg-7	1205-1400	651-760	56 Ag, 22 Cu, 17 Zn, 5 Sn
BAg-8	1435-1650	780-899	77 Ag, 23 Cu
BAg-8a	1410-1600	766-871	77 Ag, 23 Cu
BAg-13	1575-1775	857-635	54 Ag, 40 Cu, 5 Zn, 1 Ni
BAg-13a	1600-1800	871-982	56 Ag, 42 Cu, 2 Ni
BAg-18	1325-1550	718-843	60 Ag, 40 Cu
BAg-19	1610-1800	877-982	92 Ag, 8 Cu
Precious metals			
BAu-1	1860-2000	1016-1093	37 Au, 63 Cu
BAu-2	1635-1850	890-1010	79.5 Au, 20.5 Cu
BAu-3	1885-1995	1030-1090	34 Au, 62 Cu, 4 Ni
BAu-4	1740-1840	949-1004	82 Au, 18 Ni
Nickel alloys			
BNi-1	1950-2200	1066-1204	14 Cr, 3 Br, 4 Si, 4 Fe, 75 Ni
BNi-2	1850-2150	1010-1177	7 Cr, 3 Br, 4 Si, 3 Fe, 83 Ni
BNi-3	1850-2150	1010-1177	3 Br, 4 Si, 2 Fe, 91 Ni
BNi-4	1850-2150	1010-1177	1 Br, 3 Si, 2 Fe, 94 Ni
BNi-5	2100-2200	1149-1204	19 Cr, 10 Si, 71 Ni
BNi-6	1700-1875	927-1025	11 Br, 89 Ni
BNi-7	1700-1900	927-1038	13 Cr, 10 Br, 77 Ni

FIGURE 7-20 Composition and use of solders.

most common general-purpose solder. Solder selection is based on its ability to wet the surface of the base metals being joined. The grade containing the least amount of tin that provides suitable flowing and wetting action should be used. Special solders such as tin–antimony for food equipment, tin–zinc for aluminum, and lead–silver for high strength are available. Solders containing lead should not be used for drinking water systems or for food equipment.[9]

5. *Application of heat.* There are many different methods of applying the heat, and each is specifically designed for particular applications. The different methods of applying heat for soldering will be covered later in this section.
6. *Cooling the solder joint.* The joint is cooled to room temperature after the base metal surfaces have been wetted and the space between them filled with solder. Quite often, self-jigging joints are employed, or staking, bending, or other assembly methods are used. Cooling is normally accomplished by removing the heat source and utilizing an air blast.
7. *Postcleaning.* Postcleaning is necessary to remove the flux residue which may be corrosive. Certain fluxes are considered noncorrosive and may not be removed unless it affects the appearance or later processing of the part. However, for fluxes identified as corrosive, such as the acid types, it is absolutely necessary that they be removed. They should be neutralized and removed to provide for a successfully soldered joint.

   The different methods of soldering are based on the way the heat or the way that the solder is applied.

Dip Soldering

Dip soldering (DS) is a soldering process in which the heat required is furnished by a molten metal bath which provides the solder filler metal. The solder may be kept molten by any source of heat.

Furnace Soldering

Furnace soldering (FS) is a soldering process in which the parts to be joined are placed in a furnace and heated to a suitable temperature. In furnace soldering the parts must be assembled and fixed in their proper position. The solder must be preplaced in the joint. The furnace can be fired by any suitable fuel.

Induction Soldering

Induction soldering (IS) is a soldering process in which the heat required is obtained from the resistance of the work to an induced electric current. This is similar to induction brazing.

Infrared Soldering

Infrared soldering (IRS) is a soldering process in which the heat required is furnished by infrared radiation. This is similar to infrared brazing.

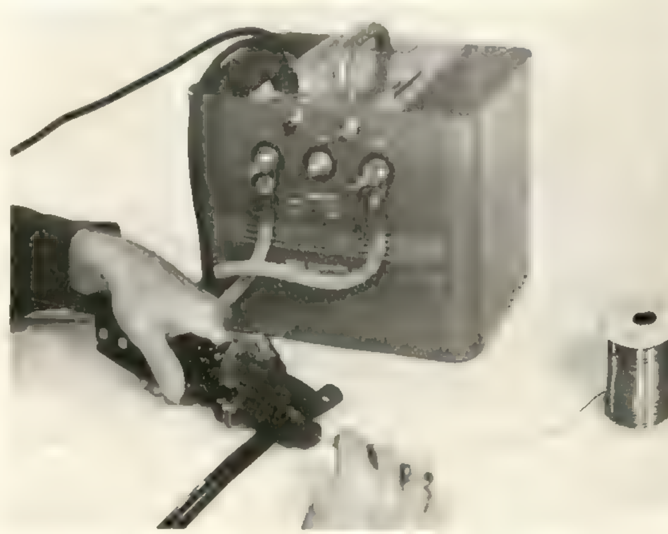
Iron Soldering

Iron soldering (INS) is a soldering process in which the heat required is obtained from a soldering iron. The part of the soldering iron which is heated and transfers the heat and the solder to the joint is called a *bit*, and is usually made of copper. The bit of a soldering iron may be heated by several different ways. It can be electrically heated by internal resistance coil—hence, the electric soldering iron, it can be heated in a flame, or it can be heated in a furnace. There is also the *soldering gun* which utilizes resistance heating to heat the bit. The bit is the high-resistance part of the electrical circuit. Soldering guns are very popular and widely used for electronic assembly work. The solder is applied manually.

Resistance Soldering

Resistance soldering (RS) is a soldering process in which the heat required is obtained from the resistance to electric current in a circuit of which the work is a part. This is slightly different from resistance brazing and is usually done with a hand-held tool using carbon blocks and introducing a low voltage and relatively high current to the part to be soldered. This is a very common method of manufacturing electrical machinery involving soldered joints. Figure 7-21 shows this soldering method in use,

FIGURE 7-21 **Resistance soldering.**



attaching lugs to welding cables. The solder is applied manually. It is also used for soldering copper plumbing fittings.

Torch Soldering

Torch soldering (TS) (Figure 7-22) is very similar to torch brazing except that lower temperatures are involved and air is used rather than oxygen. Small cylinders of propane are available for this use. The cylinder becomes the handle when a torch head is attached to it. This system is ideal for occasional use. The solder is applied manually. Torch soldering is widely used in the plumbing trade for soldering copper tubing to copper fittings.

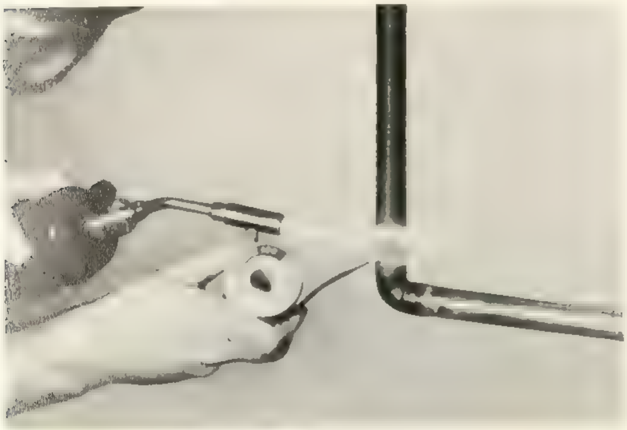


FIGURE 7-22 Torch soldering.

Wave Soldering

Wave soldering (WS) is an automatic soldering process where work parts are passed through a wave of molten solder. This method is used in the production of printed circuit boards. The circuit boards are assembled with the various electronic components on them with pigtails sticking through the circuit board and crimped over the printed metal circuit on the underside of the board. The boards are then placed over the tank holding the molten solder and the wave of solder touches the metal circuit and joins it to the pigtails of the electronic component with a soldered joint. This is completely automatic and produces high-quality soldered joints. It is widely used in the electronics industry. Figure 7-23 shows the wave soldering apparatus.

There are several other methods of soldering. One of these is *ultrasonic soldering*. It is a soldering method in which high-frequency sonic energy is transmitted through molten solder to remove undesirable surface films and promote wetting of the base metal. Flux is not normally used. In this method the ultrasonic vibrations are transmitted to the soldering iron and thereby transmitted to the solder and to the work. A source of ultrasonic energy is required as well as a specialized soldering iron. This method is used for soldering aluminum.

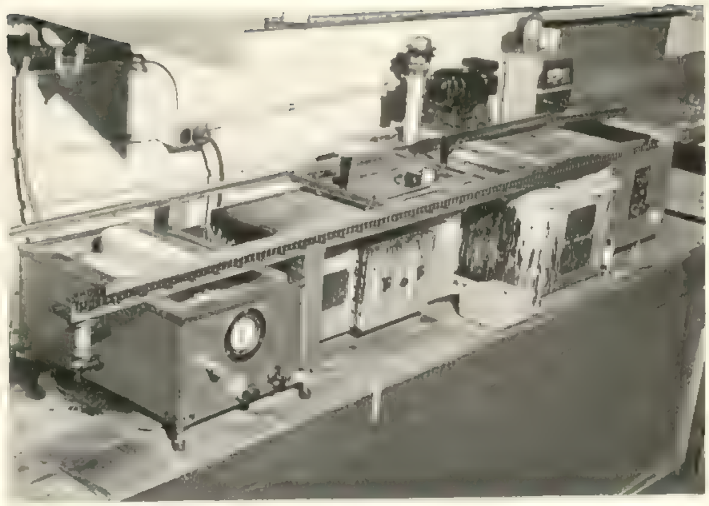


FIGURE 7-23 Wave soldering machine.

Wipe soldering is a method of producing a joint with the heat supplied by the molten solder poured onto the joint. The solder is manipulated with a hand-held cloth or paddle so as to obtain the required size and contour. The filler metal is also distributed into the joint by capillary attraction. It is similar to an old welding method known as flow welding which produces coalescence of metals by heating them with molten filler metal poured over the surfaces to be welded until the welding temperature is obtained and until the required filler metal has been added. Both wipe soldering and flow welding are of minor industrial importance today.

One other soldering method is known as *sweat soldering*. This is a method in which two or more parts are precoated with solder, assembled into a joint, and reheated without the use of additional solder. This is used in the electrical industry for joining wires to connectors.

Soldering is a very widely used metals-joining method. For more information on this subject, consult the "AWS Soldering Manual."[10]

7-4 THERMIT WELDING

Thermit welding (TW) is a welding process that produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum with or without the application of pressure. Filler metal is obtained from the liquid metal. This is one of the older welding processes. It was invented in about 1900, but is still used for specific applications.[11]

The heat for welding is obtained from an exother-

mic reaction between iron oxide and aluminum. This reaction is shown by the following formula:

$$8Al + 3Fe_3O_4 = 9Fe + 4Al_2O_3 + heat$$

The temperature resulting from this reaction is approximately 4500 °F (2500 °C). The superheated steel is contained in a crucible located immediately above the weld joint. The exothermic reaction is relatively slow and requires 20 to 30 seconds no matter how much of the chemicals are involved. The superheated steel runs into a mold which is built around the parts to be welded. Since it is almost twice as hot as the melting temperature of the base metal melting occurs at the edges of the joint and alloys with the molten steel from the crucible. Normal heat losses cause the mass of molten metal to solidify, coalescence occurs, and the weld is completed. The thermit welding process is applied only in the automatic mode. Once the reaction is started, it continues until it goes to completion. Welding utilizes gravity, which causes the molten metal to fill the cavity between the parts being welded. It is very similar to the foundry practice of pouring a casting. The difference is the extremely high temperature of the molten metal. The making of a thermit weld is shown in Figure 7-24.

The thermit material is a mechanical mixture of metallic aluminum and processed iron oxide. This mixture may also include various elements for alloying the weld metal. Thermit mixtures can be designed to produce specific weld metal deposits. The normal analysis of thermit employed to weld mild and medium carbon steel is as follows:

- Carbon 0.20–0.30
- Manganese 0.50–0.60
- Silicon 0.25–0.50
- Aluminum 0.07–0.18
- Iron balance

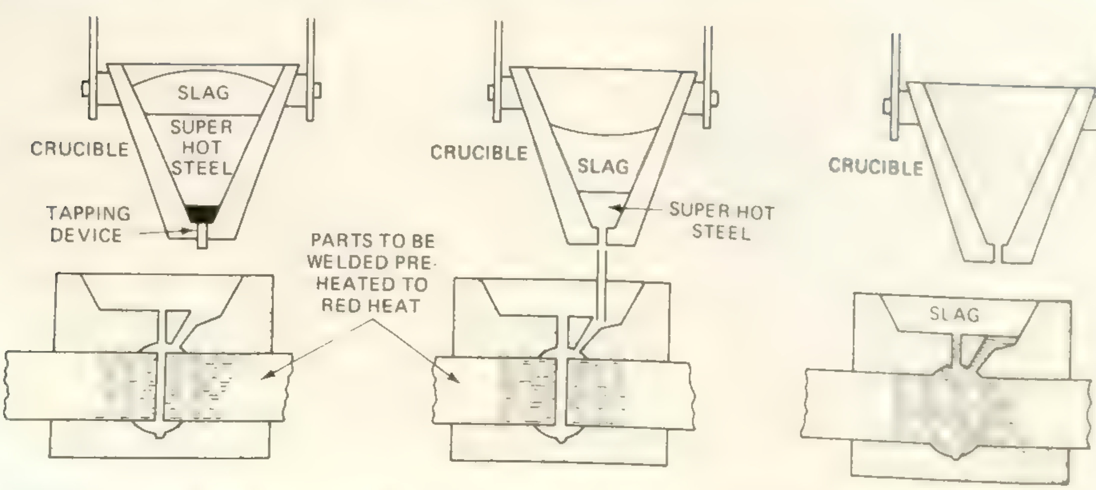
The thermit can be designed for wear resistance and for welding cast iron, as well as for welding carbon steels. The mechanical properties of normal thermit are approximately the same as those of mild steel.

The thermit powder will not ignite until it is brought to an initial temperature of 2400 °F (1300 °C). It is normally started by using a special ignition powder which creates the temperature. During the exothermic reaction the molten steel will go to the bottom of the crucible. The aluminum oxide will float to the top as a slag, which protects the molten steel from the atmosphere. The molten metal is tapped by a tapping pin at the bottom of the crucible. The superheated molten metal immediately flows into the mold through the pouring gate into the cavity making the weld. Venting must be provided to ensure that the cavity is completely filled.

The parts to be welded must be prepared with a square groove joint. The root opening between the parts is related to the cross-sectional area of the weld. The root opening should range from ¾ to 1½ in. (19 to 37 mm) for joining railroad rails. For larger sections the root opening should be greater. Parts to be welded are properly aligned and braced. A mold is then made around the joint. The lost-wax technique is sometimes employed for making molds of unusual shapes. The lost-wax method involves filling the weld joint or cavity with wax then making the mold around this assembly. A riser must be provided as well as a pouring gate. A heating gate at the lower portion of the joint is provided for preheating, which is usually required. This will melt the wax, which will run out of the mold and provide the cavity for the molten weld metal. After heating is completed, the heating gate is sealed with a plug. This process is shown, in 7-25.

The amount of thermit is calculated to provide sufficient metal to produce the weld. The amount of steel produced by the reaction is approximately one-half the original quantity of thermit material by weight and one-third by volume.

FIGURE 7-24 Step in making a thermit weld.



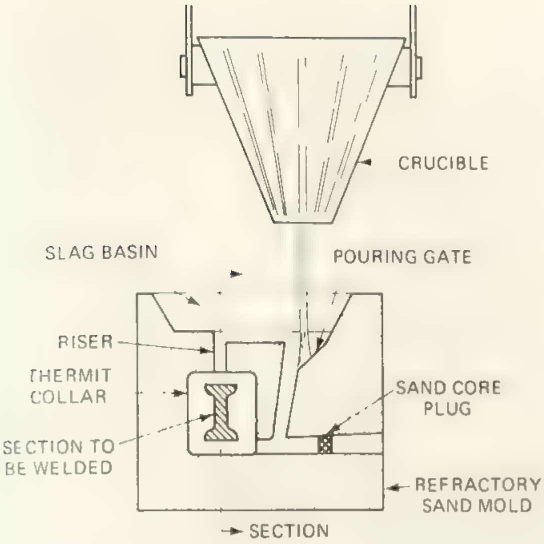


FIGURE 7-25 Details of the crucible and mold.

After the weld has cooled, the mold is broken away and discarded, and the gates and risers are removed by oxyacetylene flame cutting. The surface of the completed weld is usually sufficiently smooth and contoured so that it does not require additional metal finishing.

The resulting deposited weld metal is of the composition mentioned above, plus any alloying that may have been picked up from the parts being welded. The deposited weld metal is homogenous and quality is relatively high. Distortion is minimized since the weld is accomplished in one pass and since cooling is uniform across the entire weld cross section. There is normally shrinkage across the joint, but little or no angular distortion.

Welds can be made with the parts to be joined in almost any position as long as the cavity has vertical sides. If the cross-sectional area or thicknesses of the parts to be joined are quite large, the primary problem is to provide sufficient thermit metal to fill the cavity.

Thermit welding has been used for many special applications. An important use was the welding of stern frames for Liberty ships during World War II. These frames were so large they could not be cast in one piece and were cast in four sections, which were joined together by four thermit welds. Another application has been in the making of large crankshafts. The thermit welds were made through the cross section of the round bearings welded to throws to make the crank. Thermit welds have also been used to weld large thick I-beams and railroad and craneway rails. They have also been popular for welding reinforcing bars. Special mixtures of thermit are required for welding alloy steels of this type.

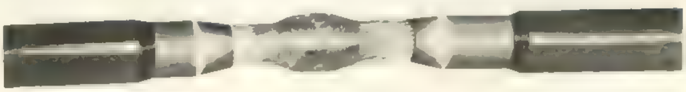
When the thermit process is used for joining rails[12] and reinforcing bars, standardized semipermanent molds are used. These molds are made in halves which are clamped around the rail or bar. The molds, which can be reused, are available for various sizes of rails and reinforcing bars. Figure 7-26 shows the welding of railroad rails.

Thermit welds are relatively inexpensive since little or no equipment is required. The primary cost is the cost of the thermit material which becomes the deposited weld metal. Thermit reinforcing bar welds meet the requirements of the Concrete Institute.

Thermit welds can also be used for welding nonferrous materials. The most popular uses of nonferrous thermit welding is the joining of copper and aluminum conductors for the electrical industry. In these cases the exothermic reaction is a reduction of copper oxide by aluminum which produces molten superheated copper. The high-temperature molten copper flows into the mold, melts the end of the parts to be welded, and as the metal cools, a solid homogenous weld results. In welding copper and aluminum cables the molds are made of graphite and can be used over and over. When welding nonferrous materials the parts to be joined must be extremely clean and a flux is normally applied to the joint prior to welding. Special kits are available that provide the molds for different sizes of cable, and provide the premixed thermit material. This material also includes enough of the igniting material so that the exothermic reaction is started by means of a special lighter. An example of thermit welds made joining heavy copper cables and for joining cables to lugs is shown in Figure 7-27.

FIGURE 7-26 Making thermit rail weld.

FIGURE 7-27 Thermit weld of copper cables.



7-5 SOLID-STATE WELDING

Solid-state welding (SSW) is a group of welding processes that produce coalescence of the faying surfaces by the application of pressure at temperatures below the melting point of the base metal without the addition of brazing or solder filler metal. Pressure may or may not be used. These processes are sometimes erroneously called solid-state bonding processes: this group of welding processes includes cold welding, diffusion welding, explosion welding, forge welding, friction welding, hot pressure welding, roll welding, and ultrasonic welding. In all of these processes, time, temperature, and pressure individually or in combination produce coalescence of the base metal without significant melting of the base metals.

Solid-state welding includes some of the very oldest of the welding processes and some of the very newest. Some of the processes offer certain advantages since the base metal does not melt and form a nugget. The metals being joined retain their original properties without the heat-affected zone problems involved when there is base metal melting. When dissimilar metals are joined their thermal expansion and conductivity is of much less importance with solid-state welding than with the arc welding processes.

Time, temperature, and pressure are involved; however, in some processes the time element is extremely short, in the microsecond range or up to a few seconds. In other cases, the time is extended to several hours. As temperature increases, time is usually reduced. Since each of these processes is different, each will be described.

Cold Welding

Cold welding (CW) is a solid-state welding process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation of the weld. Welding is accomplished by using extremely high pressures on extremely clean interfacing materials. Sufficiently high pressure can be obtained with simple hand tools when extremely thin materials are being joined. When cold welding heavier sections a press is usually required to exert sufficient pressure to make a successful weld. Indentations are usually made in the parts being cold welded. The process is readily adaptable to joining ductile metals. Aluminum and copper are readily cold welded. Aluminum and copper can be joined together by cold welding and is shown by Figures 7-28 and 7-29.

FIGURE 7-28 Copper welded to aluminum.

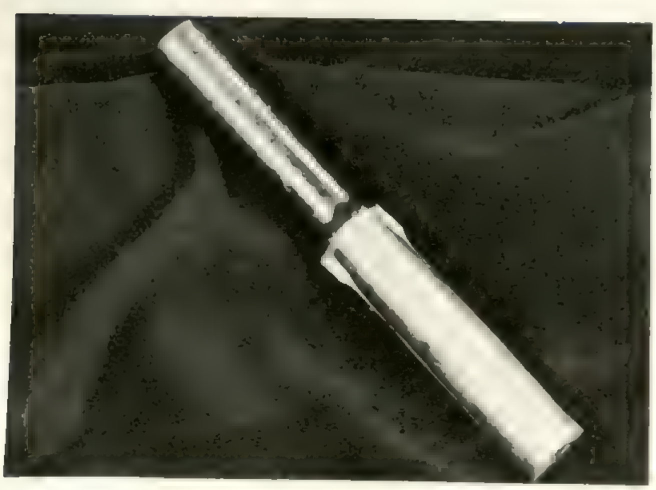
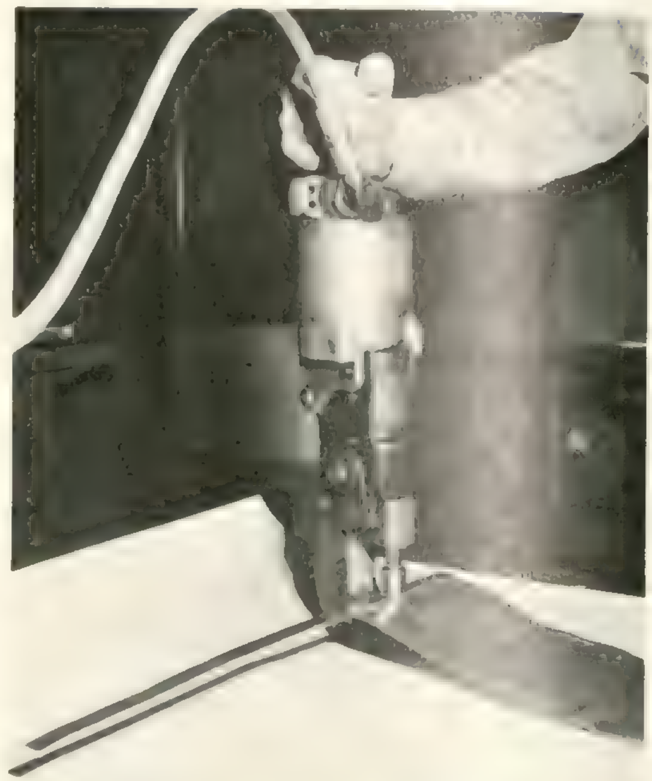
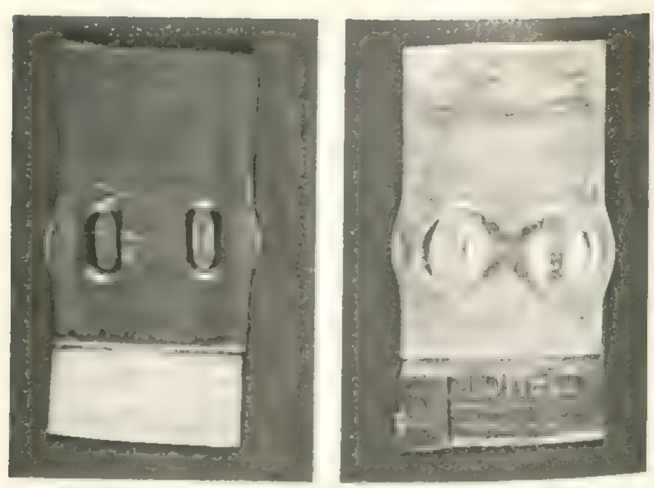


FIGURE 7-29 Making a cold weld.





Diffusion Welding

Diffusion welding (DFW) is a solid-state welding process that produces coalescence of the faying surfaces by the application of pressure at elevated temperature. The process does not involve macroscopic deformation, melting, or relative motion of the workpieces. A solid filler metal may or may not be inserted between the faying surfaces.

The process is used for joining refractory metals at temperatures that do not affect their metallurgical properties. Heating is usually accomplished by induction, resistance, or furnace. Atmosphere and vacuum furnaces are used, and for most refractory metals a protective inert atmosphere is desirable. Successful welds have been made on refractory metals at temperatures slightly over half the normal melting temperature of the metal. To accomplish this type of joining, extremely close tolerance joint preparation is required and a vacuum or inert atmosphere is used. The process is used quite extensively for joining dissimilar metals. The process is considered diffusion brazing when a layer of filler material is placed between the faying surfaces of the parts being joined. These processes are used primarily by the aircraft and aerospace industries.

Explosion Welding

Explosion welding (EXW) is a solid-state welding process in that it effects coalescence by high-velocity movement together of the workpieces produced by a controlled detonation. The explosion welding process is shown in Figure 7-30. Explosive welding was developed in the mid-1940s and the first patent was taken out in 1957.[13] Even though heat is not applied in making an explosion weld, it appears that the metal at the interface is molten during welding. This heat comes from several sources, from the shock wave associated with impact and from the energy expended in collision. Heat is also released by plastic deformation associated with jetting and ripple formation at the interface between the parts being welded. Plastic interaction between the metal surfaces is especially pronounced when surface jetting occurs. It is found necessary to allow the metal to flow plastically in order to provide a good-quality weld. The interface or weld of explosion welded parts is shown in Figure 7-31. Explosion welding creates a strong weld between almost all metals. It has been used to weld dissimilar metals that were not weldable by the arc processes. The weld apparently does not disturb the effects of cold work or other forms of mechanical or thermal treatment. The process is self-contained, it is portable, and welding can be achieved quickly over large areas. The strength of the weld joint is equal to or greater than the strength of the weaker of the two metals joined.

Explosion welding has not become too widely used except in a few limited fields. One of the most widely used applications of explosion welding has been in the cladding of base metals with thinner alloys. The photomicrograph shown in Figure 7-31 is a cross section of a weld between dissimilar metals. Another application for explosion welding is in the joining of tube-to-tube sheets for the manufacture of heat exchangers. The process is also used as a repair tool for repairing leaking tube-to-tube sheet joints. Another and new application has been the joining of pipes in a socket joint. This application will be of increasing importance in the future.

FIGURE 7-30 Explosion welding.

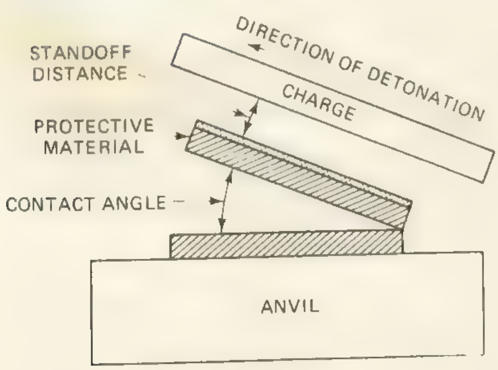


FIGURE 7-31 Interface of explosion weld.

Forge Welding

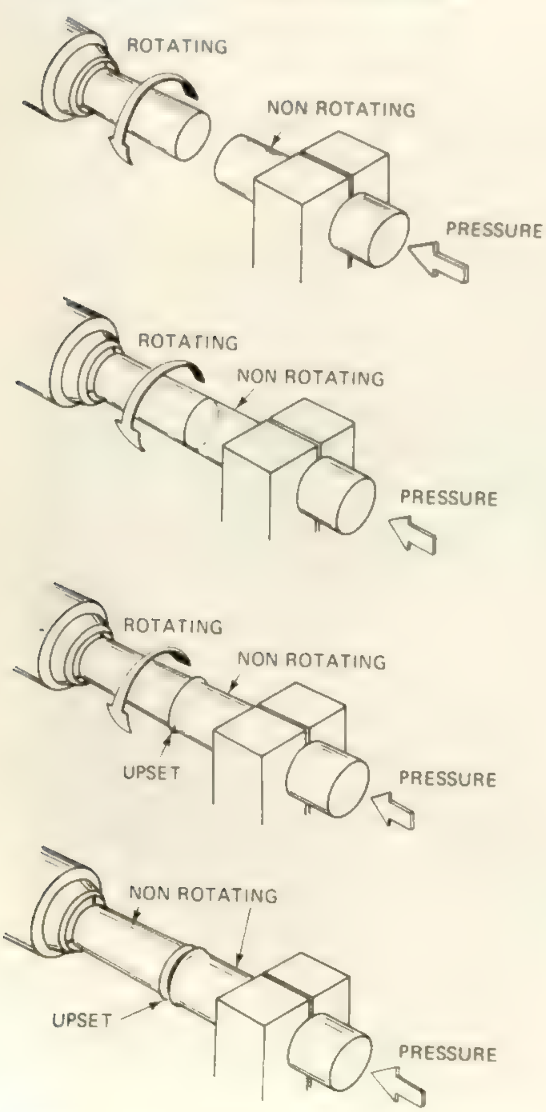
Forge welding (FOW) is a solid-state welding process that produces coalescence of metals by heating them in air in a forge and by applying pressure or blows sufficient to cause permanent deformation at the interface. This is one of the older welding processes and at one time was called hammer welding. Forge welds made by blacksmiths were made by heating the parts to be joined to a red heat considerably below the molten temperature. Normal practice was to apply flux to the interface. The blacksmith by skillful use of a hammer and an anvil was able to create

pressure at the faying surfaces sufficient to cause coalescence. This process is of minor industrial significance today.

Friction Welding

Friction Welding (FRW) is a solid-state welding process that produces coalescence of materials under compressive force contact of workpieces rotating or moving relative to one another to produce heat and classically displace material from the faying surfaces (Figure 7-32). This process usually involves the rotating of one part against another to generate frictional heat at the junction. When a suitable high temperature has been reached, rotational motion ceases and additional pressure is applied and coalescence occurs. Friction welding was developed in the Soviet Union in 1957. The results of research was published by V. I. Vill.[14] It was not until 1960 that the process was used in the United States.

FIGURE 7-32 **Friction welding process.**



There are two variations of the friction welding process. In the original process one part is held stationary and the other part is rotated by a motor which maintains an essentially constant rotational speed. The two parts are brought in contact under pressure for a specified period of time with a specific pressure. Rotating power is disengaged from the rotating piece and the pressure is increased. When the rotating piece stops the weld is completed. This process can be accurately controlled when speed, pressure, and time are closely regulated.

The other variation is called *inertia welding*. Here a flywheel is revolved by a motor until a preset speed is reached. It, in turn, rotates one of the pieces to be welded. The motor is disengaged from the flywheel and the other part to be welded is brought in contact under pressure with the rotating piece. During the predetermined time during which the rotational speed of the part is reduced, the flywheel is brought to an immediate stop and additional pressure is provided to complete the weld.

Both methods utilize frictional heat and produce welds of similar quality. Slightly better control is claimed with the original process. The two methods are similar and offer the same welding advantages

Among the advantages of friction welding is the ability to produce high-quality welds in a short cycle time. No filler metal is required and flux is not used. The process is capable of welding most of the common metals. It can also be used to join many combinations of dissimilar metals. Friction welding requires relatively expensive apparatus similar to a machine tool. Figure 7-33 shows a friction welding machine.

There are three important factors involved in making a friction weld:

1. *The rotational speed.* This is related to the material to be welded and the diameter of the weld at the interface.
2. *The pressure between the two parts to be welded.* Pressure changes during the weld sequence. At the start it is very low, but it is increased to create the frictional heat. When the rotation is stopped, pressure is rapidly increased so that forging takes place immediately before or after rotation is stopped.
3. *The welding time.* Time is related to the shape and the type of metal and the surface area. It is normally a matter of a few seconds. The actual operation of the machine is automatic and is controlled by a sequence controller which can be set according to the weld schedule established for the parts to be joined.

Normally, for friction welding one of the parts to be welded is round in cross section; however, this is not an absolute necessity. Visual inspection of weld quality can be based on the flash, which occurs around the out-

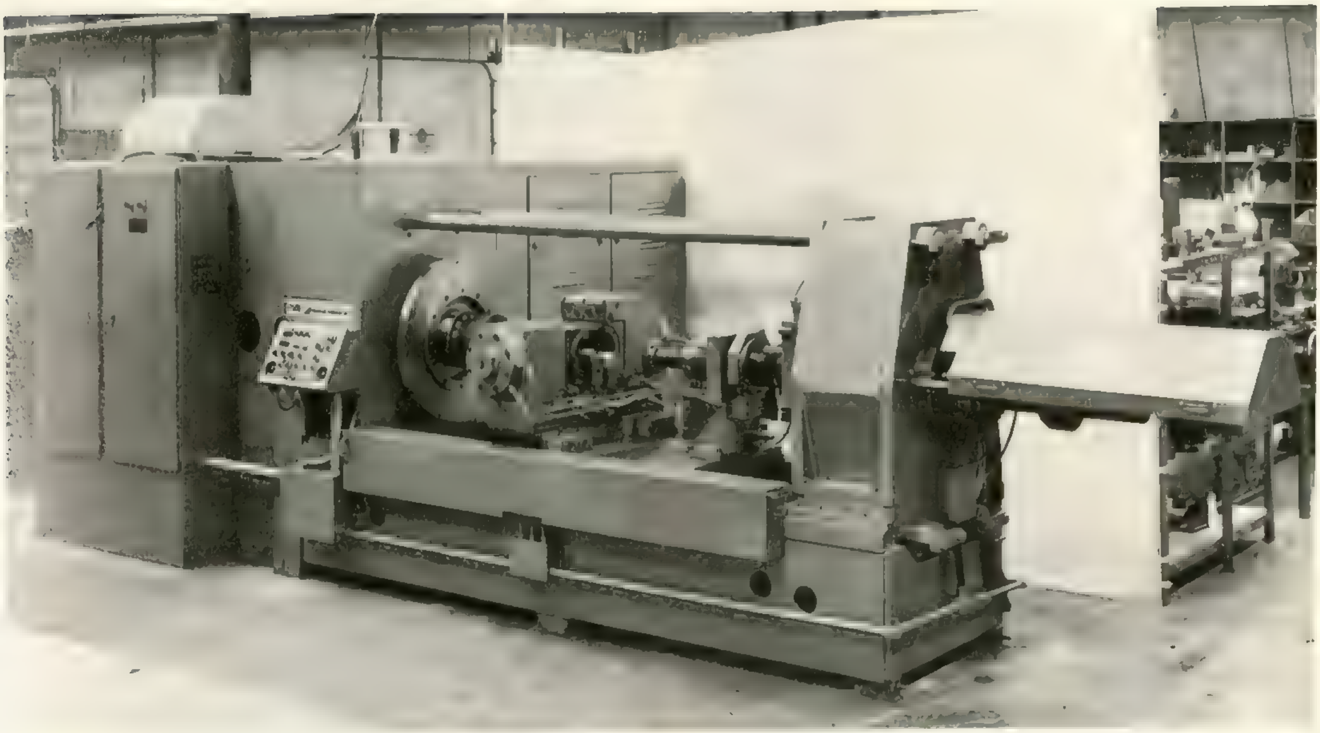


FIGURE 7–33 Friction welding machine.

side perimeter of the weld. Normally, this flash will extend beyond the outside diameter of the parts and will curl around back toward the part but will have the joint extending beyond the outside diameter of the part. If the flash sticks out relatively straight from the joint, it is an indication that the time was too short, the pressure was too low, or the speed was too high. These joints may crack. If the flash curls too far back on the outside diameter, it is an indication that the time was too long and the pressure was too high. Between these extremes is the correct flash shape. The flash is normally removed after welding. Figure 7-34 shows a circular friction welded part. Note both the inside flash and the outside flash. Provisions were made in this part so that the inner flash would not extend to inside the chamber where it might interfere with the function of the part. Figure 7-35 shows a variety of parts made by friction welding.

Hot Pressure Welding

Hot pressure welding (HPW) is a solid-state welding process that produces coalescence of metals with heat and application of pressure sufficient to produce macrodeformation of the base metal. Vacuum or other shielding media may be used.

In this process coalescence occurs at the interface between the parts because of pressure and heat, which is accompanied by noticeable deformation. The deformation of the surface cracks the surface oxide film and increases the areas of clean metal. Welding this metal to the clean metal of the abutting part is accomplished by diffusion across the interface so that coalescence of the faying surface occurs. This type of operation is normally carried on in closed chambers where vacuum or a shielding medium may be used. It is used primarily in the production of weldments for the aerospace industry. A variation is the hot isostatic pressure welding method. In this case, the pressure is applied by means of a hot inert gas in a pressure vessel.

Roll Welding

Roll welding (ROW) is a solid-state welding process that produces coalescence of metals by heating and by applying sufficient pressure with rolls to cause deformation at the faying surfaces. This process is similar to forge welding except that pressure is applied by means of rolls rather than by means of hammer blows. Coalescence occurs at the interface between the two parts by means of diffusion at the faying surfaces.

One of the major uses of this process is the cladding of mild or low-alloy steel with a high-alloy material such as stainless steel. It is also used for making bimetallic materials for the instrument industry. It is used to produce the *sandwich* coins used in the United States. Figure 7-36 is a photomicrograph of the weld of a coin made in this manner. This is a weld between copper and a nickel–copper alloy.

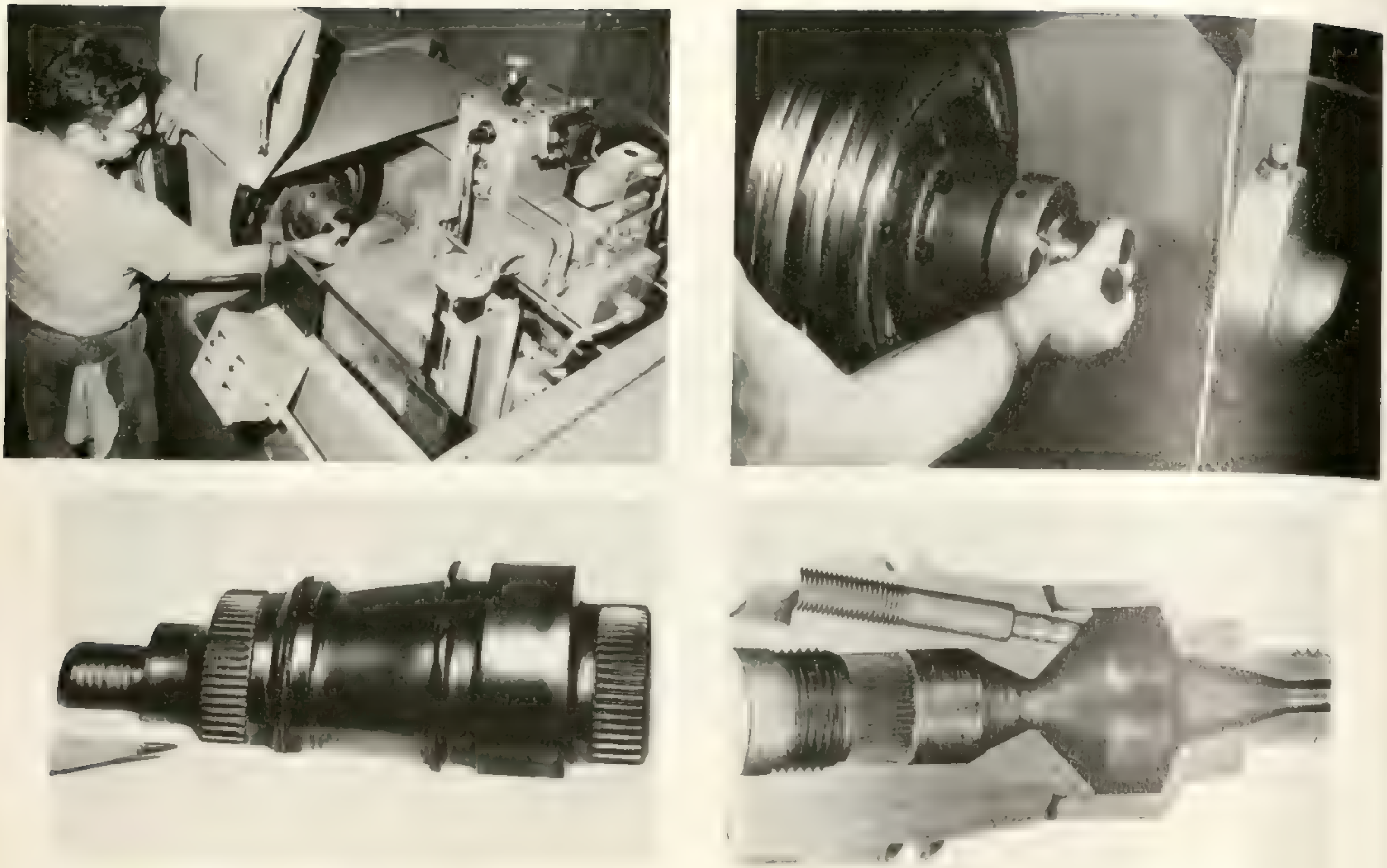
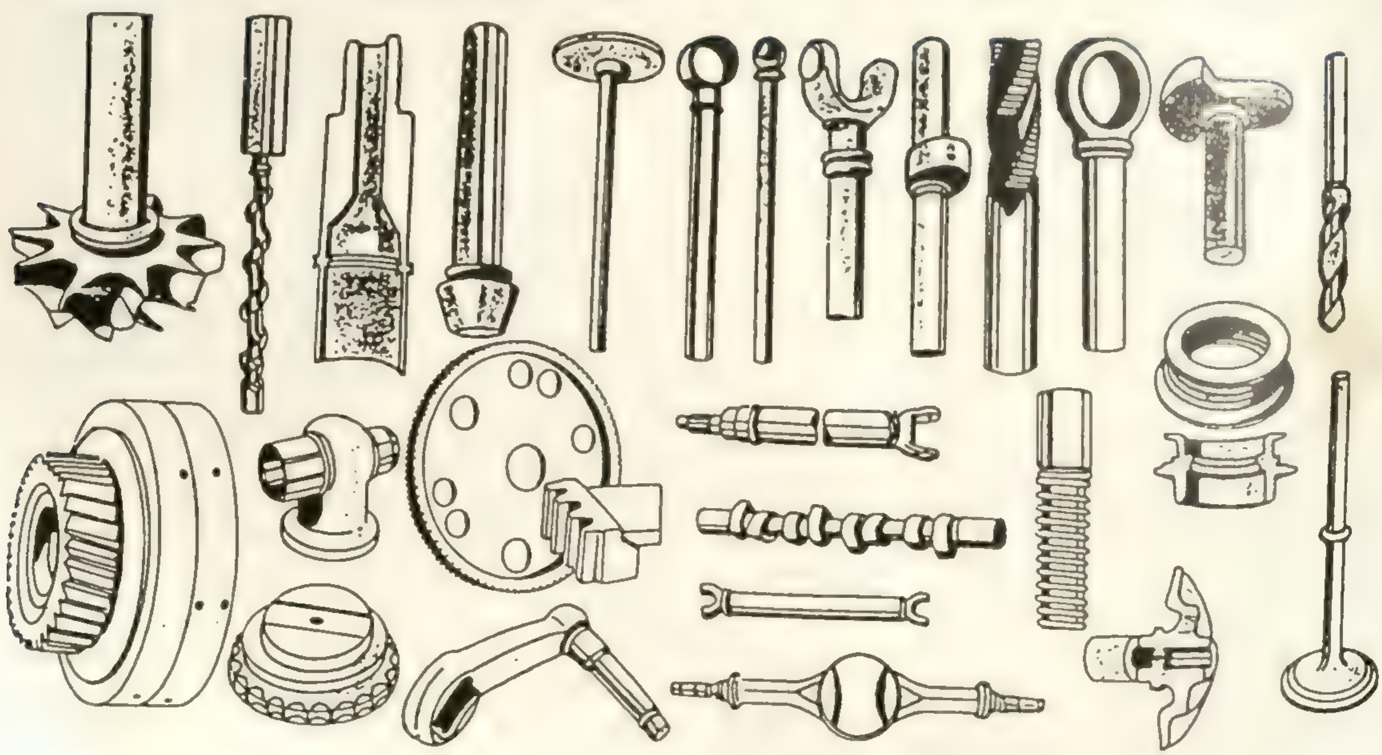


FIGURE 7-34 Part friction welded.

FIGURE 7-35 Parts assembled by friction welding.



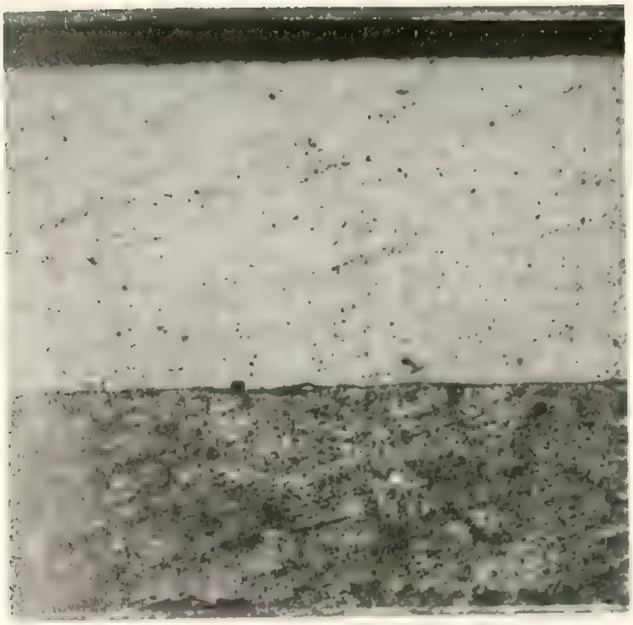


FIGURE 7-36 Interface of roll weld.

Ultrasonic Welding

Ultrasonic welding (USW) is a solid-state welding process that produces coalescence of materials by the local application of high-frequency vibratory energy as the workpieces are held together under pressure. Welding occurs when the ultrasonic tip or electrode, the energy-coupling device, is clamped against the work pieces and is made to oscillate in a plane parallel to the weld interface. The combined clamping pressure and oscillating forces introduce dynamic stresses in the base metal. This produces minute deformations which create a moderate temperature rise in the base metal at the weld zone. This coupled with the clamping pressure provides for coalescence across the interface to produce the weld. Ultrasonic energy will aid in cleaning the weld area by breaking up oxide films and causing them to be carried away. The vibratory energy that produces the minute deformation comes from a transducer which converts high-frequency alternating electrical energy into mechanical energy. The transducer is coupled to the work by various types of tooling which can range from tips similar to resistance welding tips to resistance roll welding electrode wheels. The normal weld is the lap joint weld.

The temperature at the weld is not raised to the melting point and therefore there is no nugget similar to resistance welding. Weld strength is equal to the strength of the base metal. Most ductile metals can be welded together and there are many combinations of dissimilar metals that can be welded. The process is restricted to relatively thin materials normally in the foil or extremely thin gauge thicknesses.[15]

This process is used extensively in the electronics, aerospace, and instrument industries. It is also used for producing packages and containers and for sealing them. Figure 7-37 shows an ultrasonic weld being made by continuous seam welder. In this picture a rotating electrode is the active welding tip which delivers ultrasonic energy to the work. The process can also be used for joining plastics and is finding wider use in this field than in joining metals.

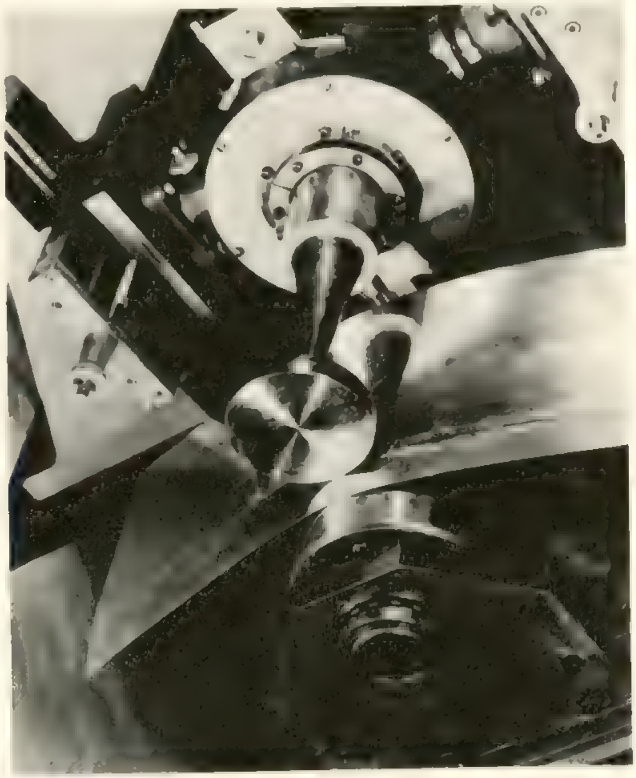


FIGURE 7-37 Ultrasonic welding.

7-6 MISCELLANEOUS WELDING PROCESSES

The "other welding processes" include induction welding, flow welding, ionic welding, and solar welding, among others. These are processes of limited application, processes of little industrial significance, or processes too new to have been defined by the American Welding Society.

Flow Welding

Flow welding (FLOW) is a braze welding process variation that uses the heat from molten filler metal poured over the fusion faces. This is an obsolete or seldom-used process.

Induction Welding

Induction welding (IW) is a welding process that produces coalescence of metals by the heat obtained from the resistance of the workpieces to the flow of induced high-frequency welding current with or without the application of pressure. The effect of high-frequency welding current is to concentrate the welding heat at the desired location.

Plasma MIG Welding

A new welding process developed by Philips in Holland in 1971 is named plasma-MIG welding.[16] It is a combination of gas metal arc welding and plasma arc welding. The standard plasma torch is modified by placing the tungsten electrode slightly to one side of the center line of the torch and nozzle orifice. A contact tip is inserted in the torch on this centerline and a continuous wire is fed to the tip and through the nozzle orifice along with the plasma gas. In other words, the gas metal arc consumable electrode and the arc itself are contained within the plasma column. Separate power supplies are used—one for the plasma and one for the electrode wire. Under certain conditions the gas metal arc rotates within the plasma. Extremely high temperatures are attained and this results in high deposition rates.

Of necessity, the torch is larger than a standard plasma torch and more complex. In addition, an extra power source is employed plus extra circuitry for starting the process. In view of this, it is normal to move the work under a fixed torch. One major application for the process is cladding of steel with dissimilar material such as stainless steel. This process is still very new, has not attained sufficient use, and is therefore of little industrial application.

Induction brazing and induction soldering are similar in that the heating is done by inducing currents within the workpiece, which, in turn, create heating within the workpiece. High-frequency resistance welding is similar; high-frequency current is transmitted to the workpiece by means of sliding shoes. The high-frequency current creates heating on the surfaces to be welded. Induction welding is a combination of these two. The high-frequency current is introduced into the workpiece by means of induction but the frequency is sufficiently high that it is concentrated on the surface of the work, particularly the surfaces to be welded. Welding is accompanied by pressure and filler metal is not used. The availability of extremely high frequency generating equipment has made this process possible.

The high-frequency current required is in the range 200,000 to 500,000 Hz. The power is generated by means of vacuum tube or solid-state oscillators. The generator has a power output of from 1 to 600 kW, depending on the range of material thicknesses and production requirements. The output of the oscillator is fed into coils which have few turns and are water cooled. The work coil induces the high-frequency current to flow in the closely coupled workpiece. The coil must be designed for the particular work to be done.

The induced high-frequency current flows on or near the surface of the workpiece and heat is generated only in the section of the base metal that carries the current. A relatively small amount of base metal is brought to the welding temperature. The resistance of the workpiece to the induced current causes the heating. The heated surfaces become sufficiently hot so that with sufficient pressure a weld is made, and, as it cools, coalescence occurs.

One of the most common uses of the process is the making of pipe and tubing. It is also used for joining dissimilar metals and can be used for making butt or lap seams of strip or sheet ranging from the very thinnest to sheet metal gauge thicknesses. This process is normally automatic and is used for high-volume production of similar joints or parts.

Ion Beam Welding

Ion beam welding has not been developed to practical use as yet. It is somewhat similar to electron beam welding and heat is created by the bombardment of ions on the surface to be welded. The reason for interest in ion beam welding is that it has different characteristics from electron beam welding. Ion bombardment, which is used in gas tungsten arc welding for the cleaning action, would become part of this welding process. The ion beam is less sensitive to external magnetic fields than the electron beam and there is no x-radiation. To make this process practical, it is necessary to have a source of ions, to accelerate the beam of ions to the workpiece, and to be able to focus the beam on the weld area. Efforts to perfect this process are progressing in the laboratories, and perhaps in the not-too-distant future, welding will be performed with ion beams.

Solar Energy Welding

All the various beam-type welding processes are highly concentrated sources of energy. The energy is utilized to heat metals so that welding can be accomplished. The sun is well known as a source of heat, and for many years there have been solar furnaces used to melt metals. This is accomplished by focusing the sun's rays with a parabolic mirror to a crucible. The major factor in solar welding is the use of a *heliostat*, which is a device utilizing the mirrors moved by clockwork for directing the sun's rays to a constant point. The rays are directed into a parabolic mirror which deflects them to form a small focal spot. The focal spot is then directed to the work and concentrated to the actual welding point. Welding

is accomplished by moving the workpiece with respect to the stationary focal spot. Fixturing, travel mechanisms, and so on, are similar to those used by the other welding processes. To prevent the atmosphere from coming in contact with the molten base metal, the weld area is shielded by an inert gas. Welds have been made successfully on material from 0.039 to 0.118 in. (1 to 3 mm) thick in a single pass. Filler metal was not utilized. Travel speeds up to 2 in. (50 mm) per minute have been accomplished. Welds have been made in stainless steels with qualities equal to the base metal. So far this process is a laboratory curiosity. It may become useful in certain parts of the world, depending on the availability of solar energy.

Spot-Adhesive Welding

Spot-adhesive welding combines spot welding with adhesives to produce joints that are stronger, more durable, and more resistant to fatigue than joints produced by either method alone. This process has been called *weld bonding* and has been used on aircraft structures.

It is practiced by the application of an adhesive in paste form to the faying surfaces of the weld joint. Resistance spot welds are made through the lap joints. The weldment is then heated in an oven to cure the adhesive. Another variation of the process is accomplished by first making the spot weld joint and then applying the adhesive at the edge of the joint, and, by means of capillary action, the adhesive flows between the faying surfaces and around the resistance spot welded nuggets. After the adhesive dries the assemblies are placed into an oven for curing. The process has been used on aluminum for aircraft subassemblies. The strength of the weld bond joints apparently is determined by the strength of the adhesive that is used.

Ultra Pulse Welding

Ultra pulse welding is a resistance type of welding process which uses an extremely short weld time. The principle of operation is that of a capacitor which is charged from the power lines and discharged through a transformer and by means of resistance-type electrodes to the work. The charging time is relatively long compared to the discharge or welding time which is in the order of a few milliseconds. The advantage of this system is that it reduces power line draw and makes welds in an extremely short time. Heat does not build up in the workpiece. It is used for welding extremely small and thin parts. The process is used for producing electronic components and instruments.

Other Welding Processes

There are other welding processes that have been used but today are of little industrial significance. These processes are defined and briefly described in the AWS "Standard Welding Terms and Definitions."[17]

Undoubtedly, there are other welding processes that will be invented and introduced in the future. Some of the currently used processes will fall into disuse. These continuing changes will ultimately help produce weldments at lower costs.

QUESTIONS

7-1. Where is the hottest part of the oxyacetylene flame?

7-2. What is produced by the secondary reaction besides heat and CO_2?

7-3. What are the three types of flames?

7-4. Why shouldn't you use a cigarette lighter to light the welding torch?

7-5. Explain the operation of a gas pressure regulator.

7-6. Does brazing require the use of a filler metal that has a higher or lower melting temperature than the base metal?

7-7. Is it possible to obtain a brazed joint stronger than the filler metal?

7-8. What is preplaced filler metal?

7-9. What are the three types of oxyacetylene flames? How is each produced?

7-10. What is the difference between a single- and a two-stage regulator?

7-11. Why shouldn't oil or grease be used on an oxygen apparatus?

7-12. Is flux required for making oxyacetylene welds on clean mild steel? Why?

7-13. What is the difference between soldering and brazing?

7-14. Why is flux required for soldering?

7-15. Explain how gravity is used in making a thermit weld.

7-16. Is it possible to thermit weld copper or aluminum?

7-17. Can cold welding be applied manually?

7-18. The clad coins of the United States are sometimes made by what welding process?

7-19. Explain the difference between friction welding and cold welding.

7-20. Can ultrasonic welding be applied to plastics as well as to thin metals?

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8

Resistance, Electron Beam, and Laser Beam Welding

OUTLINE

8-1 RESISTANCE WELDING

"Resistance welding (RW): a group of welding processes that produce coalescence of the faying surfaces with the heat obtained from resistance of the work to the flow of the welding current in a circuit of which the work is a part and by the application of pressure." There are at least eight different resistance welding processes and many variations. They are as follows:

- Flash welding (FW)
- Percussion welding (PEW)
- Projection welding (PW)
- Resistance seam welding (RSEW)
  - High frequency (RSEW-HF)
  - Induction (RSEW-I)
- Resistance spot welding (RSW)
- Upset welding (UW)
  - High frequency (UW-HF)
  - Induction (UW-I)

In addition, there is resistance brazing, which uses a filler metal.

Practical spot welding was invented by Elihu Thomson of Massachusetts in 1877. It took several years before it was adopted by industry. In the early 1880s it was being used commercially and was called "incandescent welding." Thomson went on to develop other resistance welding processes.

The resistance welding processes share a common definition, but many of them are considerably different. The more important processes and variations will be explained.

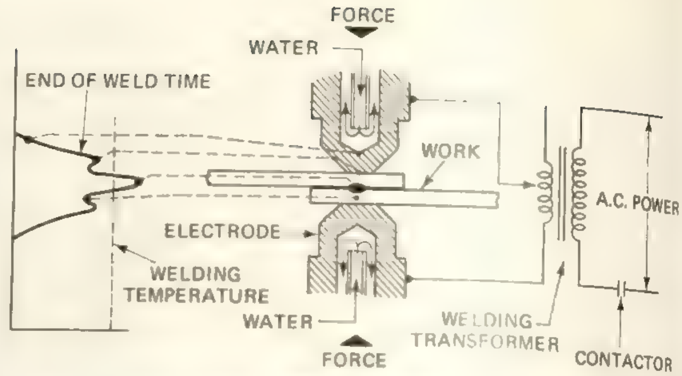


FIGURE 8-1 **Resistance spot welding process.**

Principles of Operation

The resistance welding processes differ from arc welding in that pressure is used but filler metal or fluxes are not. Four factors are involved in making a resistance weld. They are (1) the amount of current that passes through the work, (2) the pressure that the electrodes transfer to the work, (3) the time the current flows through the work, and (4) the area of the electrode tip in contact with the work. Heat is generated by the passage of electrical current through a resistance circuit. The maximum amount of heat is generated at the point of maximum resistance, which is at the surface between the parts being joined. The high current, up to 100,000 A at low voltage, generates sufficient heat at this resistance point so that the metal reaches a plastic state. The force applied before, during, and after the current flow forges the heated parts together so that coalescence will occur. Pressure is required throughout the entire welding cycle to assure a continuous electrical circuit. The amount of current employed and the time period are related to the heat input required to overcome heat losses and raise the temperature of the metal to the welding temperature.

The concept of resistance welding is most easily understood by relating it to resistance spot welding. Spot welding, the most popular, is shown in Figure 8-1. High current at a low voltage flows through the circuit in accordance with Ohm's law:

$$I = \frac{E}{R} \text{ or } R = \frac{E}{I} \text{ or } E = I \times R$$

where I = current in amperes
E = voltage in volts
R = resistance of the materials in ohms

The total energy is expressed by the formula. Heat energy H equals $I \times E \times T$, in which T is the time in seconds during which current flows in the circuit. Combining these two equations gives

$$H \text{ (heat energy)} = I^2 \times R \times T$$

For practical reasons a factor that relates to heat losses should be included; therefore, the actual resistance welding formula is

$$H \text{ (heat energy)} = I^2 \times R \times T \times K$$

where I = current in amperes
R = resistance of the work in ohms
T = time of current flow in seconds
K = heat losses through radiation and conduction

Welding heat is proportional to the square of the welding current. If the current is doubled, the heat

generated is quadrupled. Welding heat is proportional to the total time of current flow. If current is doubled, the time can be reduced, which is recommended. The welding heat generated is directly proportional to the resistance, which is related to the material being welded, the contact area, and the pressure applied. Mechanical pressure, which forces the parts together, helps refine the grain structure of the weld.

Heat is also generated at the contact between the welding electrodes and the work. This amount of heat generated is lower since the resistance between high-conductivity electrode material and the work is less than that between the two workpieces. In most applications the electrodes are water cooled to minimize the heat generated.

Resistance welds are made very quickly; however, each process has its own time cycle. Resistance welding operations are automatic. Good-quality welds do not depend on welding operator skill but more on the proper setup and adjustment of the equipment and adherence to weld schedules. The position of making resistance welds is not a factor, particularly when welding thinner materials.

Resistance welding is widely used by the mass-production industries, where production runs and consistent conditions are maintained. Welding is performed with operators who normally load and unload the welding machine and push the switch to initiate the weld operation. The automotive industry is the major user followed by the appliance industry. It is used by many industries manufacturing a variety of products made of thinner-gauge metals and for manufacturing pipe, tubing, and smaller structural sections. Resistance welding has the advantage of producing a high volume of work at high speeds that are reproducible with high quality.

Weldable Metals

Metals that are weldable, the thicknesses that can be welded, and joint design are related to specific resistance welding processes. Most of the common metals can be welded by many of the resistance welding processes (Figure 8-2). However, difficulties may be encountered when welding certain metals in thicker sections. Some metals require heat treatment after welding for satisfactory mechanical properties. Weldability of a metal is controlled by three factors: (1) resistivity, (2) thermal conductivity, and (3) melting temperature. The metal with a high resistance to current flow and with a low thermal conductivity and a relatively low melting temperature are easily weldable. Ferrous metals all fall into this category. Metals that have a lower resistivity but a higher thermal conductivity will be slightly more difficult to weld, and this includes the light metals—aluminum and magnesium. The precious metals are difficult to weld because of the very high thermal conductivity. The refractory metals, which have extremely high melting points, are more difficult to weld.

These three properties can be combined into a formula that will provide an indication of the ease of welding a metal. This formula is

$$W = \frac{R}{FKt} \times 100$$

where W = weldability

R = resistivity

F = melting temperature of the metal in °C

Kt = relative thermal conductivity with copper equal to 1.00

If W (weldability) is below 0.25, it is a poor rating. If W is between 0.25 and 0.75, weldability becomes fair. Between 0.75 and 2.0 weldability is good, and above 2.0 weldability is excellent. In this formula mild steel would have a weldability rating of over 10. Aluminum has a weldability factor of from 0.75 to 2, depending on the alloy, and these are considered having a good weldability rating. Copper and certain brasses have a low weldability factor and are known to be very difficult to weld.[1] This information applies primarily to spot welding, but would be an indication for the other resistance welding processes where arcing does not take place.

Metal	Weldability	Weldability Rating
Aluminums	Weldable	0.75–2+
Magnesium	Weldable	1.80
Inconel	Weldable	2+
Nickel	Weldable	2.15
Brass and bronze	Variable weldable	0.5–10+
Monel	Weldable	2+
Precious metals	Variable weldable	0.16–3.0
Low-carbon steel	Weldable	10+
Low-alloy steel	Weldable	10+
High- and medium-carbon steel	Possible	10+
Titanium	Weldable	50+
Stainless steel	Weldable	35+

FIGURE 8-2 Metals weldable by the spot welding process.

There are more coated metals being spot welded. This includes zinc-coated, tin-coated (tern), aluminum-coated, electro-coated, painted material, and plastic-coated materials. These add to the complication of making spot welds, and in general require more sophisticated control systems. In addition, the electrode tips deteriorate much more quickly when welding coated sheet metal. Special procedures and techniques have been developed for coated steels.

Resistance Spot Welding

"Resistance spot welding (RSW): a resistance welding process that produces coalescence at the faying surfaces of a joint by the heat obtained from resistance to the flow of welding current to the workpieces from electrodes that serve to concentrate the welding current and pressure at the weld area." This was shown by the first figure. The size and shape of the individually formed spot welds are determined primarily by the size and contour of the electrodes. Spot welding is the most popular of the resistance welding processes and is described in more detail. The basic concepts pertaining to equipment, controls, electrodes, pressure application, and mechanization are generally true of the other processes.

A spot welding system needs at least the following components:

- ☐ Welding transformer for supplying power
- ☐ A means of applying pressure
- ☐ A controller/contactor
- ☐ Electrode tips for conducting welding current to the work

Welding machines are designed to include all of these functions, and they come from the very smallest to extremely large complex machines.

Spot Welding Machines

Spot welding machines can be considered in two categories: single-point or single-spot machines and multiple-spot machines. Single-spot machines can be relatively simple and inexpensive. The simplest is manually operated rated at 2 kVA with a short circuit current of 6000 A and capable of welding 20-gauge and thinner carbon steel. Such a light-duty hand-operated machine is shown in Figure 8-3. Machines of this type are used for maintenance, automobile body repair, and other light-duty operations.

The more popular machines are stationary single-spot welding machines of either the horn or rocker arm type, or the press type. The horn-type machines have a pivoted or rocking upper electrode arm which is actuated by either the operator's physical power or by air or hydraulic power. They are used for a wide variety of work, but are restricted to 50 kVA and are used for thinner gauge. Figure 8-4 shows this type of machine.

For heavier requirements, press-type machines are used. This type of machine, shown in Figure 8-5, is normally rated at 50 kVA and up. In the press-type machine, the upper electrode moves in a slide. The pressure and

FIGURE 8-3 Manually operated spot welding gun.

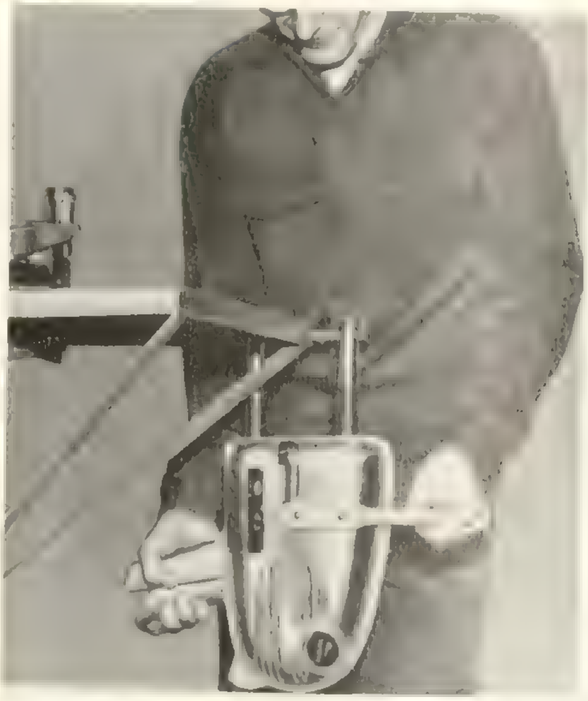
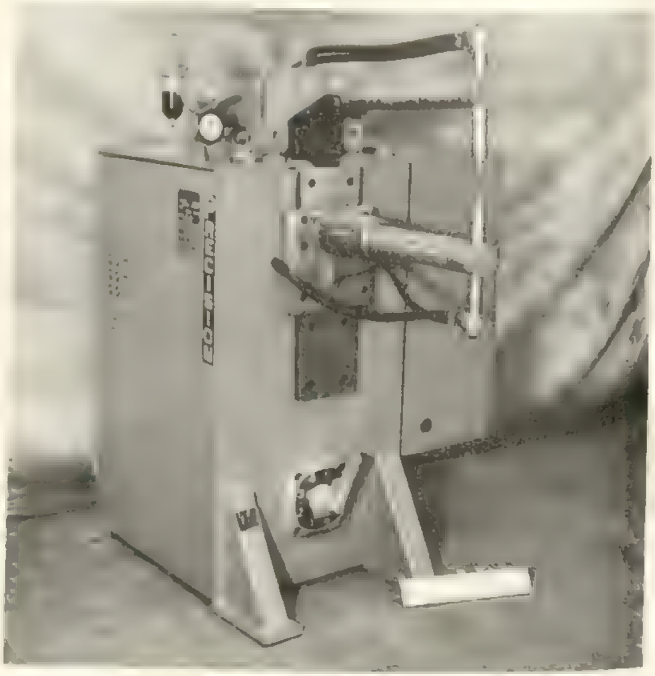


FIGURE 8-4 Rocker arm spot welding machine.



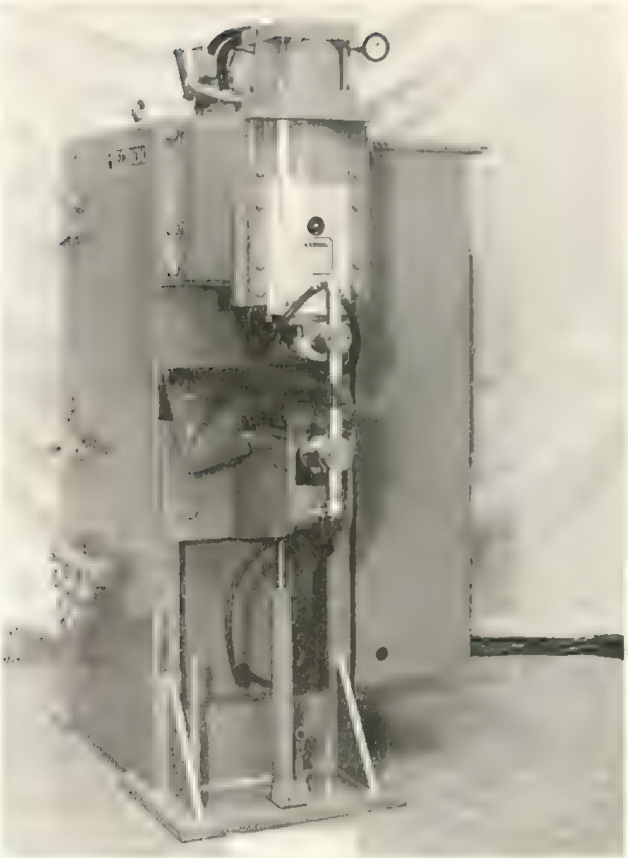


FIGURE 8-5 Press-type spot welding machine.

motion are provided on the upper electrode by hydraulic or pneumatic pressure, or are motor operated. Press resistance welding machines are used for welding medium-gauge up to the heaviest-gauge materials.

Both the press and rocker arm machines include the welding transformer. The transformer must be closely coupled to the upper and lower electrodes. The control circuit is usually in a separate enclosure mounted on the side of the machine. For all but the smallest machines, water cooling is used to cool the electrodes. The Resistance Welder Manufacturers Association has standardized and classified the standard spot welders.[2] This information is shown in Figure 8-6, which gives the size, the kVA rating, and throat depth. A resistance welding machine rated according to RWMA standards would have a 50% duty cycle. Thus a 30-kVA RWMA machine provides 30 kVA for 30 seconds of every minute, operating continuously without overheating. Machines not rated to RWMA standards may be built to a lower duty cycle, rated as little as 10 to 30%, and will overheat at higher duty cycles unless used at reduced power. The resistance welding handbook also provides the size of welding machines required to weld different metals and metal thicknesses.

When the work is too bulky to take to the welding machine, a portable spot welding machine can be used. The portable machine is moved from one welding location or fixture to another, and a trigger on the gun actuates the welding cycle. Portable units are normally operated by air or hydraulic pressure. There are two types

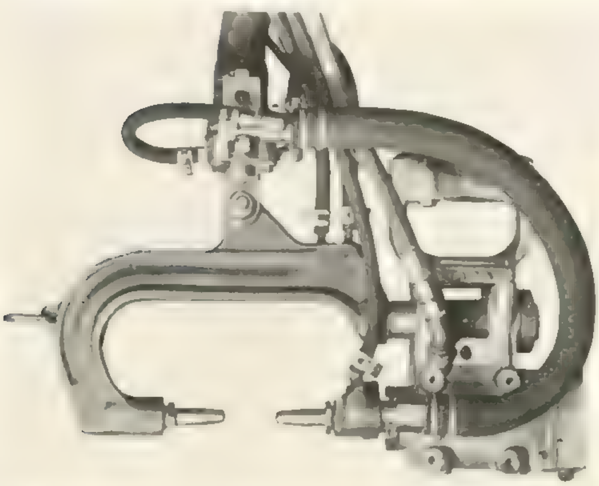
Type of Welding Machine	Size RWMA	Rating KVA	Electrode Cooling	Nominal Throat Depth (in.)
	000	5	Air	8, 12, 16
Rocker-arm spot	00	7.5	Air	8, 12, 16
welding machines	0	10	Air	8, 12, 16
	1	15	Air or Water	12, 18, 24
			Water	12, 18, 24, 30, 36
	2	30	Water	12, 18, 24, 30, 36
	3	50		
	000	5	Water	6, 8
	00	20	Water	6, 8
	0	30		
		50	Water	6, 8
	1	30		
Press-type spot &		50		
project welding		75	Water	12, 18, 30, 24, 36
machine		100		
	2	150	Water	12, 18, 24, 30, 36
		150		
	3	200	Water	12, 18, 24, 30, 36
		300		
	4	400		
		500	Water	12, 18, 30

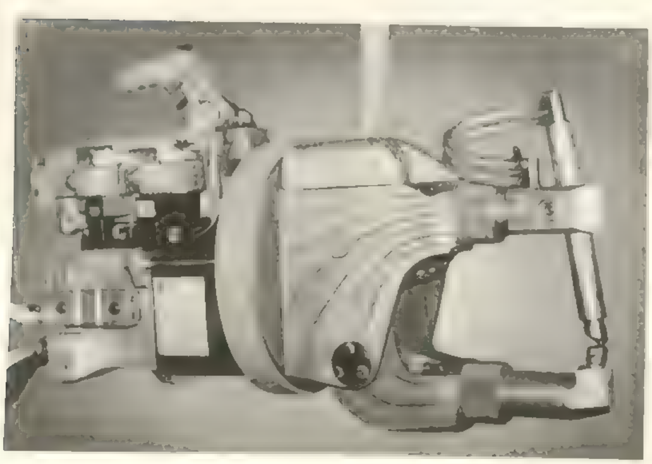
FIGURE 8-6 RWMA standard spot and projection welding machines. (From Ref. 2.)

of portable welding guns. In one case, the welding transformer is separated from the welding gun; the welding gun has its own pressure mechanism (Figure 8-7a). The portability of this type of machine is limited by heavy cables connected between the gun and the transformer. The cables are usually coaxial, to avoid movement due to magnetic forces. In the smaller machines, the transformer is included as a part of the gun (Figure 8-7b). For many years the guns were manually manipulated by the operator. The weight of the gun is handled by a balancing mechanism, but the location is established by the operator (Figure 8-8a). One of the early applications of robotic spot welding was the manipulation of the welding gun by a robot. This type of application is becoming more widely used in the automotive industries (Figure 8-8b).

The extreme application of spot welding guns by robots is shown in Figure 8-9. This shows a complete automobile body line spot welded by robots. Each gun will move around and make many spot welds. The robot always makes the spot welds in the same sequence, and produces higher-quality welds than do individual operators. Robotic spot welding of auto body lines produces more accurate bodies than previously. Almost all auto bodies produced today are made on robotic lines similar to this.

FIGURE 8-7 Portable spot welding guns.





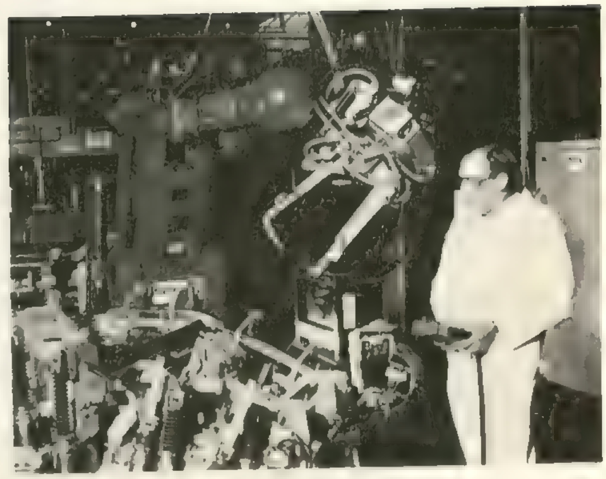
For high-volume production work such as subassemblies in the automotive industry, multiple-spot welding machines are used. These are generally in the form of a press in which individual guns carrying electrode tips are mounted. Welds are made in a sequential order so that all electrodes are not carrying current at the same time. Figure 8-10 illustrates two typical multiple-spot welding machines. They must be designed for a particular product and are thus considered dedicated machines. However, in press welders the major part that is changed for model changeover is the platen that carries the welding guns. Each individual gun has its own hydraulic piston, so that it can be moved, pressure applied, and retracted independently.

The controller-contactor is the brains of the welding system. It can be extremely simple from merely an on/off timer to an extremely complex controller that includes steady or pulsed current, preheat current, postheat current, varying levels of pressure for different time periods, and other features. A welding program using pulsed current and postweld heat treatment is shown in Figure 8-11. New-type controllers include computers and adaptive control, which reads signals produced at the tips to vary the welding schedule. Controllers for seam welding also include travel-speed mechanisms for moving the part through the electrode tips. There are controllers that use the stored-energy concept, and others that use three-phase power. The more complex controllers are used for welding aluminum and for welding coated steels. Improvements are being made on controllers, and it is thus wise to obtain information from the various manufacturers.

The working part of the resistance welding machine is the electrode. The electrode is the means for conducting welding current to the work and for providing the force necessary to make welds and for dissipating some of the heat generated. Resistance welding electrodes, the electrode holders, and the electrode material specifications are standardized by the Resistance Welders Manufacturers Association.[3] This standard separates the electrode composition into two basic groups: group A, copper-base alloys, with five classes; and group B, refractory metal compositions, also with five classes. These various groups and classes identify the analysis of the electrode alloy and relate it to electrode hardness, strength, and conductivity. RWMA recommends different electrode materials for welding different metals.

RWMA provides a method that identifies standard straight tips by a five-digit code (Figure 8-12). The taper relates to the taper on the end of the electrode and the taper in the electrode holder. This fit must be watertight

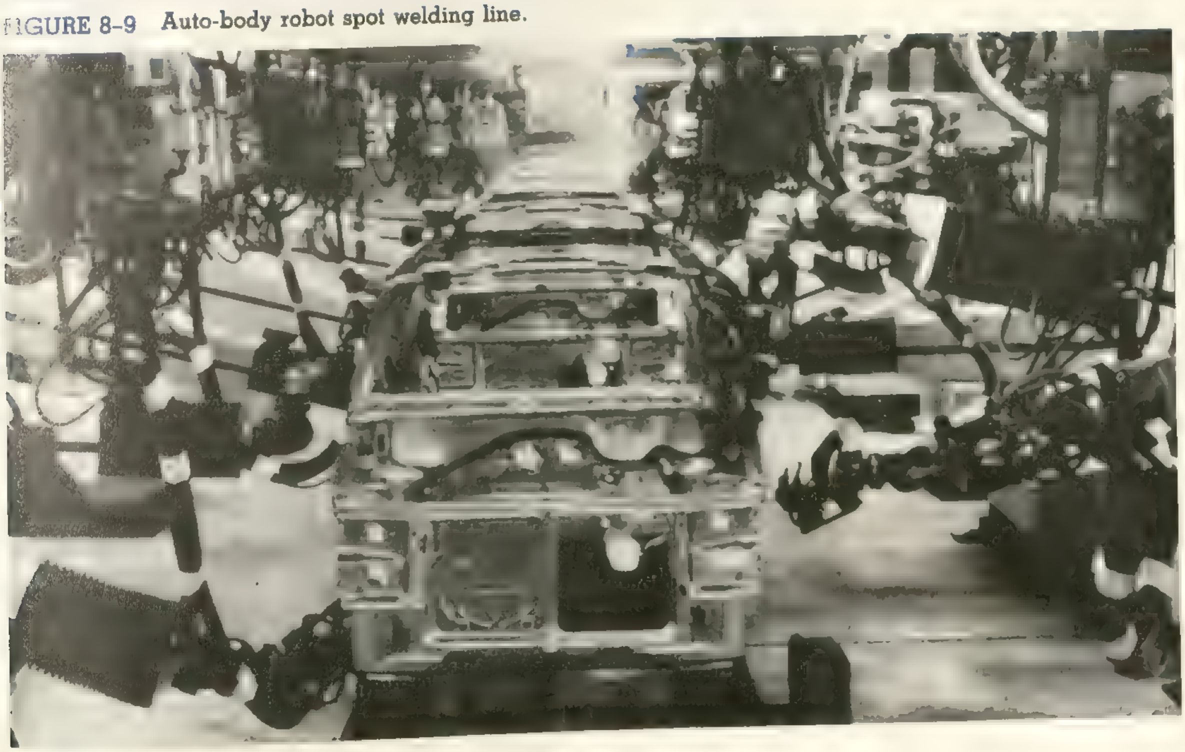
(a)

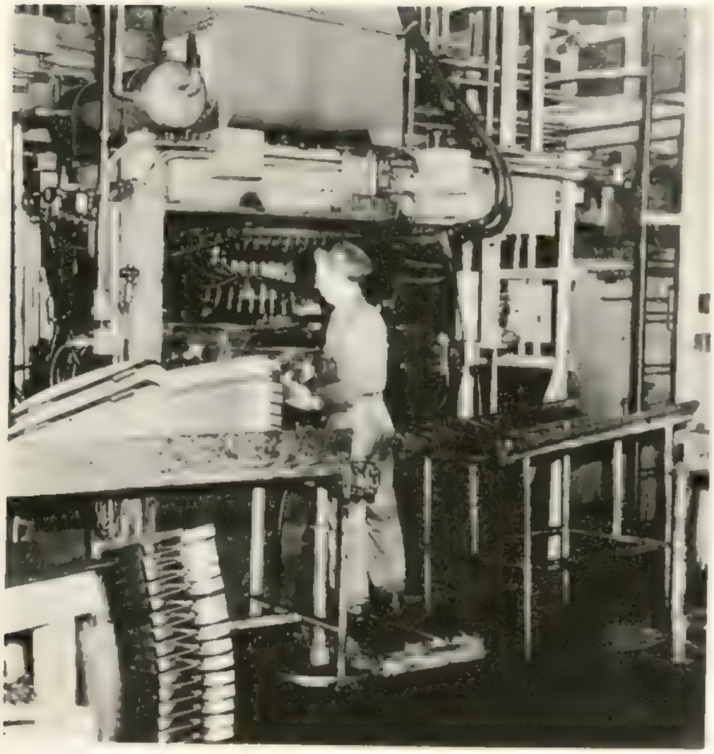


(b)

FIGURE 8-8 Portable spot welding guns in use: (a) manual; (b) robot.

FIGURE 8-9 Auto-body robot spot welding line.





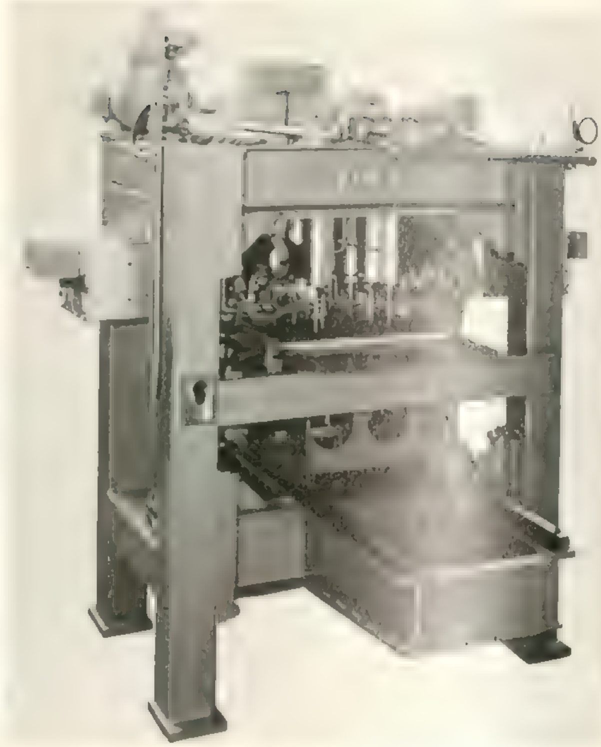
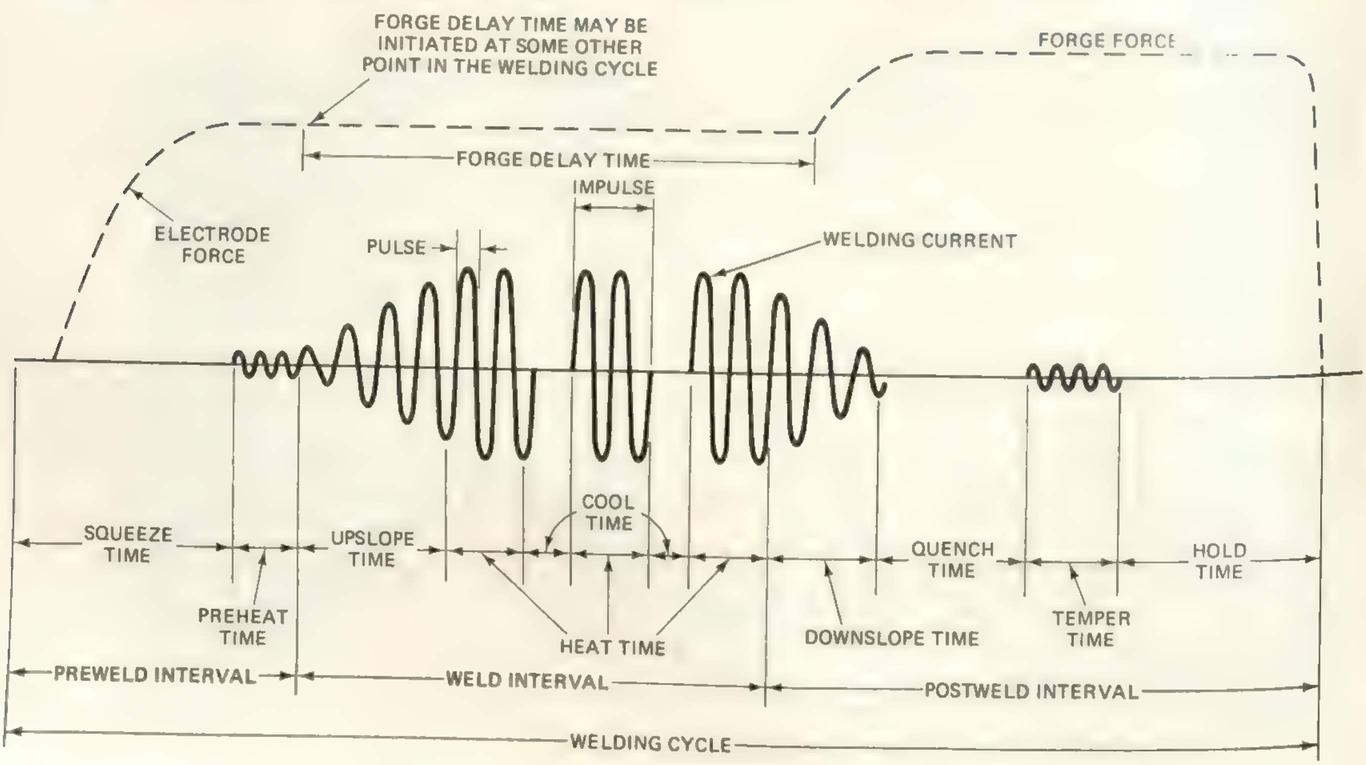
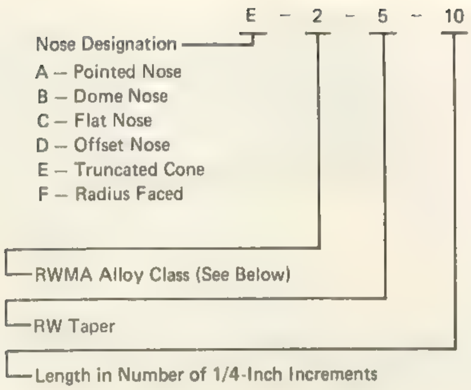


FIGURE 8-10 Multiple spot welding machines.

FIGURE 8-11 Resistance welding program.





Group	Class	Conductivity (%)	Hardness Rockwell	Tensile Compressive (psi)
A	1	80	65B	60K
	2	75	75B	65K
	3	45	90B	100K
	4	20	33C	140K
	5	10 to 15	65 to 85B	65 to 75K
B	10	35	72B	135K
	11	28	94B	160K
	12	27	98B	170K
	13	30	69B	200K
	14	30	85B	200K

FIGURE 8-12 **RWMA alloy class and standard straight tips description.**

and provides an area to transfer the welding current from the holder to the electrode. Normally, electrodes are straight, but bent tips and double-bent tips are available. Many special electrodes are made particularly for gun welders. The straight-type electrode holders are also standardized, some with an ejector tube and some without. There are also offset holders and other features. Various companies supply electrodes and electrode holders to RWMA standards and to special requirements.

Joint Types

The joint type used most often for spot welding is the lap joint. The joint overlap has a minimum requirement, which is based on the nugget size, which is related to the electrode size. The distance from the centerline of the nugget to the edge of the sheet, known as the *edge distance*, should be at least 1½ times the nugget diameter. The separation between sheets being welded should not exceed 10% of the thinnest sheet. Design parameters for spot welding are given in the resistance welding handbook.

Butt joints can also be accomplished with resistance welding processes. This is the only joint for flash butt and upset welding. However, high-frequency welding can accomplish butt welds and T welds. The T weld is used for making small beams in high-frequency resistance welding mills. Another joint, known as the lip joint, is a flanged joint. The flange width should be sufficient to allow spot welding.

The spacing of spot welds and the spacing of roll seam welds are important. If the nuggets overlap, the joint will be watertight. If they do not, water can escape between the nuggets. The resistance welding handbook also provides the size of welding machines required to weld different metals and metal thicknesses.

Spot Weld Quality

Each resistance spot weld nugget is expected to be perfect. The test used has been to pull the parts apart. If the nugget pulled out of the base metal, it is a good-quality spot weld. If it fails in any other manner, it is a subquality weld. Many specifications require destructive tests to be made after a prescribed number of welds, in the meantime, monitoring the input power, the welding current, and pressure. To assure a good-quality product, many users make double the number of spot welds specified, assuming that there would be some subquality welds produced. This procedure is expensive; therefore, automatic monitoring meters are used which will shut the equipment down when any of the parameters exceed specific values. Another quality assurance method is an adaptive welding control system that uses special sensing devices. These systems are based on the motion of the electrode during the welding cycle to monitor the growth of the weld nugget, or a change in the resistance welding or the expulsion limit. The adaptive controls will modify the welding parameters to correct weld problems.

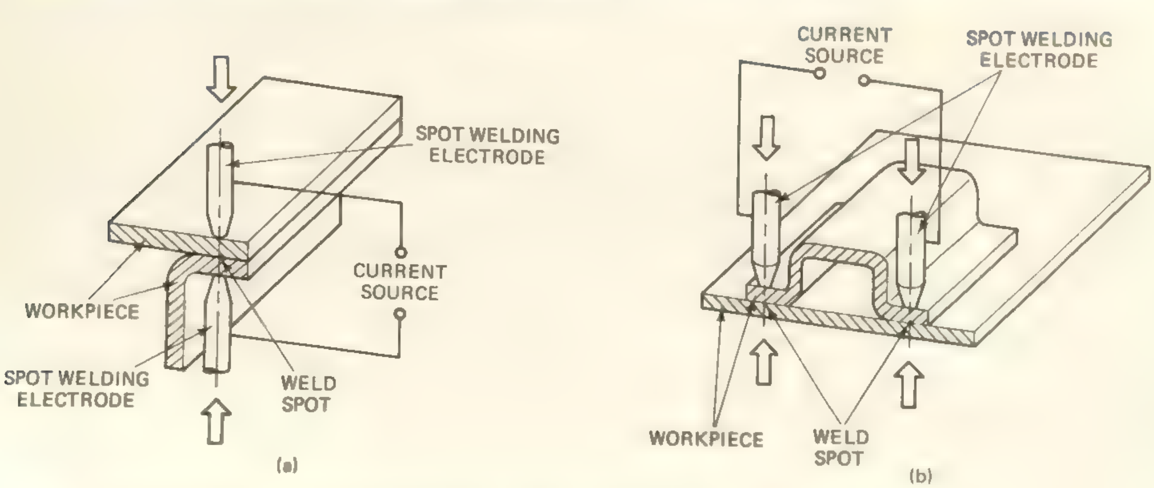
High-quality welds require continuous maintenance of the electrode tip contour. The tip or nose must be redressed often to maintain the proper shape. This must be done more often when welding highly conductive or coated materials. Special power tools (Figure 8-13) are available for redressing electrodes in the resistance welding machine. Another requirement is to check the tip pressure (Figure 8-14).

Spot welds are normally direct spot welds where the two electrodes are opposite each other, with the work to be welded between them. This may cause marking at the point where the electrode is in contact with the work. To avoid this, or where the back side of the joint is not accessible, the indirect spot is used (Figure 8-15). In this case, both electrodes are applied from one side and a large flat, or contoured, electrode is on the back side. This technique is used in the automobile industry to minimize metal finishing of exposed spot welds.

FIGURE 8-13 Dressing spot welding electrodes.

FIGURE 8-14 Electrode force meter.

FIGURE 8-15 (a) Direct and (b) indirect spot welds.

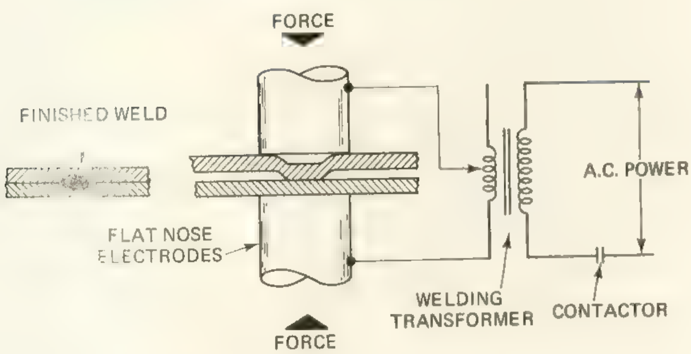


Projection Welding

"Projection welding (PW): a resistance welding process that produces coalescence by the heat obtained from the resistance to the flow of the welding current. The resulting welds are localized at predetermined points by projections, embossments, or intersections."

Figure 8-16 shows the principles of projection welding. Localization of heating is obtained by a projection or embossment on one or both of the parts being welded. There are several types of projections: (1) the button or dome type, usually round; (2) elongated projections; (3) ring projections; (4) shoulder projections; (5) cross-wire welding; and (6) radius projection. The major advantage of projection welding is that electrode life is increased because larger contact surfaces are used. A very common use of projection welding is the use of special nuts that have projections on the portion of the part to be welded to the assembly. These are manufactured with the projections and assist in obtaining good-quality joints to the parts being welded. Projection dimensions must be properly designed since the height and area have optimum dimensions for welding to specific thicknesses of sheet metal. These data are in the "Resistance Welding Manual." A press-type resistance welding machine is normally used. Flat nose or special electrodes are used.

FIGURE 8-16 Projection welding.



One of the most common variations of projection welding is wire-to-wire welding, where they cross at approximately 90°. This is used for making gratings, wire shelves, and similar items. A machine for making cross-wire welds is shown in Figure 8-17.

Resistance Seam Welding

"Resistance seam welding (RSEW): a resistance welding process that produces coalescence at the faying surfaces of overlap parts, progressively along the length of a joint. The weld may be made with overlapping weld nuggets, a continuous weld nugget, or by forging the joint as it is heated to the welding temperature by resistance to the flow of the welding current." The resulting weld is a series of overlapping spot welds made progressively along a joint by rotating the electrode. The resistance seam welding process is shown in Figure 8-18. A resistance seam welding machine is shown in Figure 8-19.

When the spots are not overlapped enough to produce gastight welds, it is a variation known as "roll resistance spot welding." This process differs from spot welding since the electrodes are wheels. Both the upper and lower electrode wheels are powered. Pressure is applied in the same manner as a press-type welder. The wheels can be either in line with the throat of the machine or transverse. If they are in line, it is normally called a

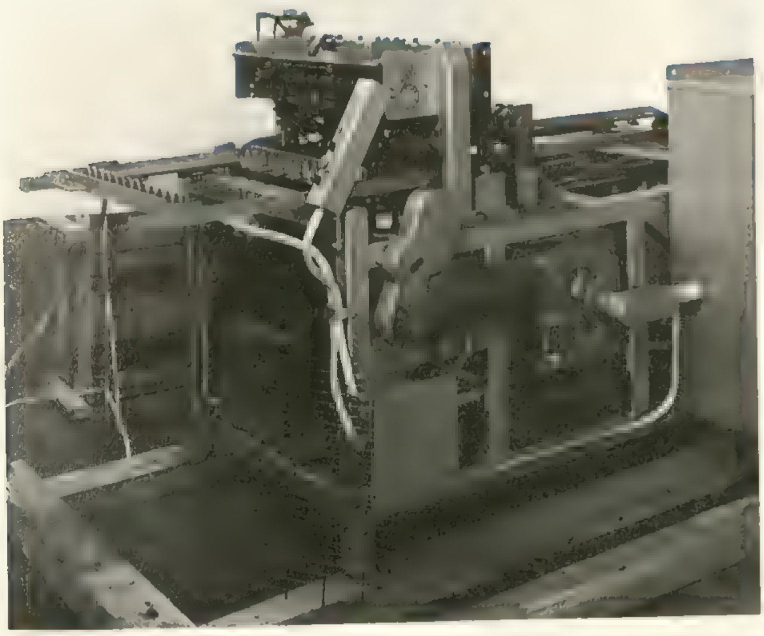


FIGURE 8-17 Cross-wire welding.

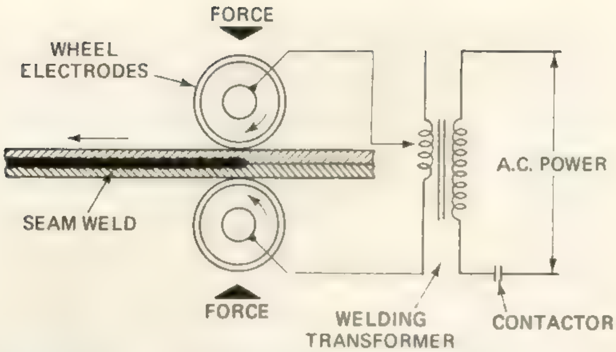
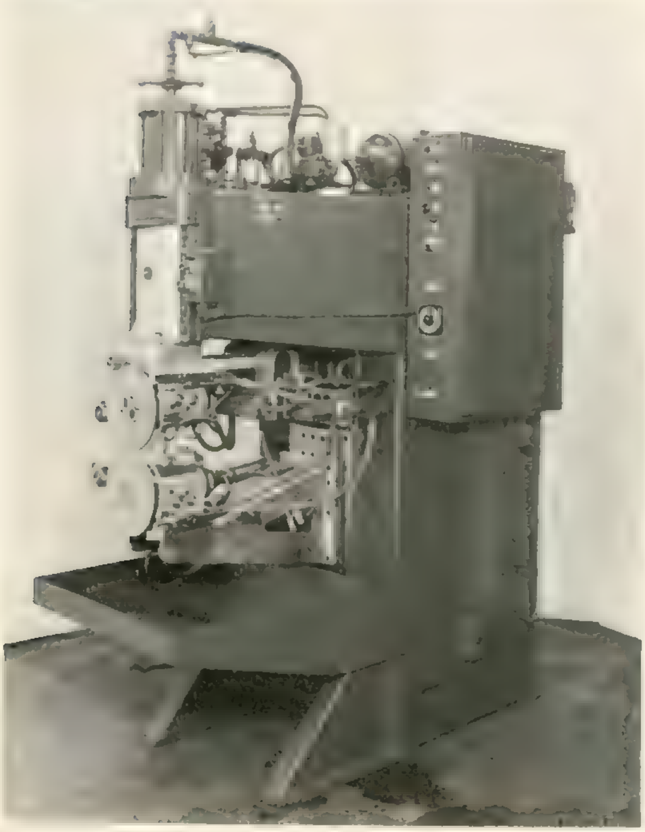


FIGURE 8-18 **Resistance seam welding process.**

FIGURE 8-19 **Resistance seam welding machine.**



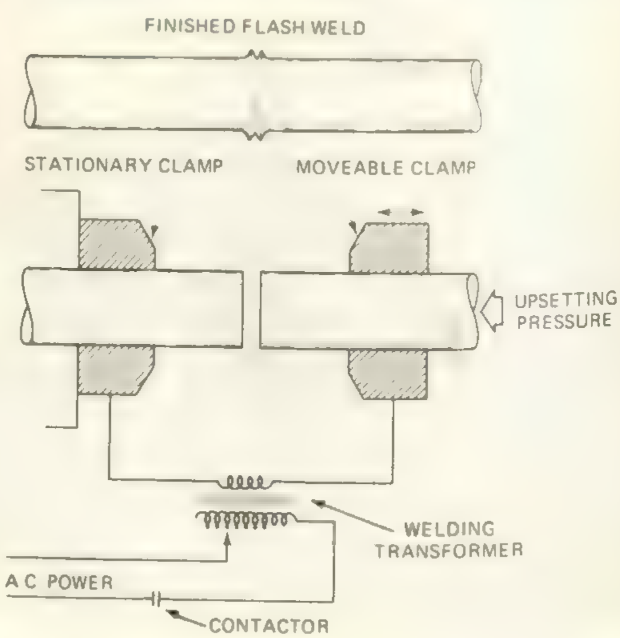
longitudinal seam welding machine. Welding current is transferred through the bearings of the roller electrode wheels. Water cooling is not provided internally, and therefore the weld area is flooded with cooling water to keep the electrode wheels cool. In seam welding a rather complex control system is required. The welding speed, the spots per inch, and the timing schedule are dependent on each other. Welding schedules provide the pressure, the current, the speed, and the size of the electrode wheels. This process is quite common for making flange welds, for making watertight joints for tanks, and so on. Another variation is the so-called mash seam welding, where the lap is fairly narrow and the electrode wheel is at least twice as wide as used for standard seam welding. The pressure is increased to approximately 300 times normal pressure. The final weld mash seam thickness is only 25% greater than the original single sheet.

Another variation for welding coated steel utilizes a round copper wire which is fed between the electrode roll and the work. It is formed into an oval by the pressure in the machine. A wire is required for both wheel electrodes. It is the copper wire that is in contact with the work rather than the electrode. The continuously fed copper wire carries the melted coating away from the weld area and provides uniform resistance for consistent welds. The flattened copper wire is discarded and salvaged as copper scrap. It eliminates coated metal pickup on the roller electrodes and is claimed to give more consistent welding results.

Flash Welding

"Flash welding (FW): a resistance welding process that produces coalescence at the faying surfaces of a butt joint by flashing action and by the application of pressure after heating is substantially completed (Figure 8-20). The flashing action caused by the very high current densities at small contact points between the workpieces forcibly expels the material from the joint as the workpieces are slowly moved together. The weld is completed by a rapid upsetting of the workpieces." The flashing and upsetting are accompanied by expulsion of metal from the joint. This is very dramatic and is shown in Figure 8-21. After a predetermined time the two pieces are forced together and coalescence occurs at the interface; current flow is

FIGURE 8-20 **Flash welding process.**



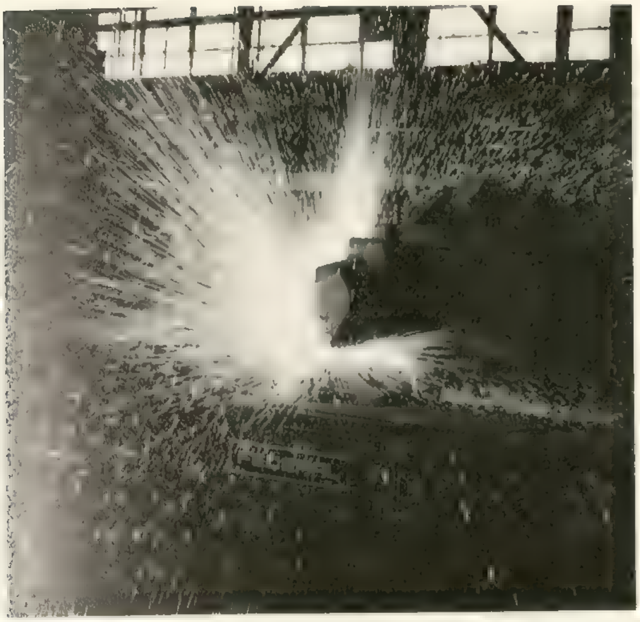


FIGURE 8-21 Flash weld being made.

possible because of the light contact between the two parts being flash welded. The heat is generated by the flashing and is localized in the area between the two parts. The surfaces are brought to the melting point and expelled through the abutting area. As soon as this material is flashed away, another small arc is formed, which continues until the entire abutting surfaces are at the welding temperature. Pressure is then applied and the arcs are extinguished and upsetting occurs.

Flash welding can be used on most metals. No special preparation is required except that heavy scale, rust, and grease must be removed. The joints must be cut square to provide an even flash across the entire surface. The material to be welded is clamped in the jaws of the flash welding machine with a high clamping pressure. The upset pressure for steel exceeds 10,000 psi (700 kg/cm²). For high-strength materials these pressures may be doubled. For tubing or hollow members the pressures are reduced. As the weld area is more compact, upset pressures are increased. If insufficient upset pressure is used, a porous, low-strength weld will result. Excess upset pressure will result in expelling too much weld metal and upsetting cold metal. The weld may not be uniform across the entire cross section, and fatigue and impact strength will be reduced. The speed of upset—that is, the time between the end of the flashing period and the end of the upset period—should be extremely short, to minimize oxidation of the molten surfaces. In the flash welding operation a certain amount of material is flashed or burned away. The distance between the jaws after welding compared to the distance before welding is known as the burn-off. It can be from ⅛ in. (3.2 mm) for thin material up to several inches for heavy material.

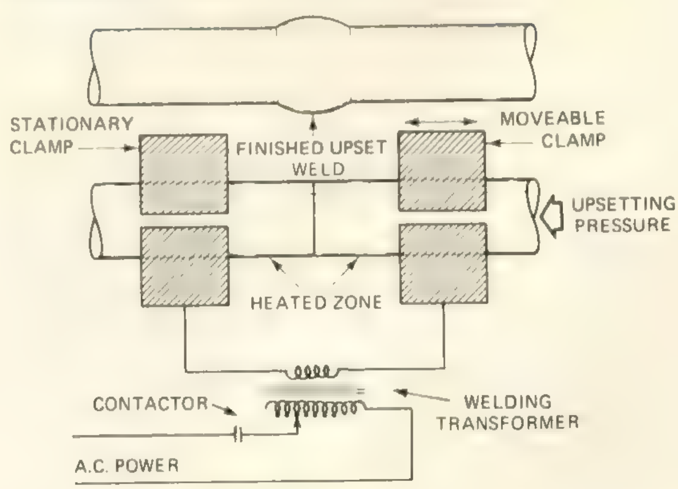
Welding currents are high and are related to the following: 50 kVA per square inch of cross section at 8 seconds. It is desirable to use the lowest flashing voltage at a desired flashing speed. The lowest voltage is normally 2 to 5 V per square inch of cross section of the weld.

The upsetting force is usually mechanical cam action. The design of the cams is related to the size of the parts being welded. Flash welding is completely automatic and is an excellent process for mass-produced parts. It requires a machine of large capacity designed specifically for the parts to be welded. Flash welds produce a fin around the periphery of the weld, which is normally removed.

Upset Welding

"Upset welding (UW): a resistance welding process that produces coalescence over the entire area of faying surfaces or progressively along a butt joint by the heat obtained from the resistance to the flow of welding current through the area where those surfaces are in contact. Pressure is used to complete the weld." Pressure is applied before heating is started and is maintained throughout the heating period (Figure 8-22). The equipment used for upset welding is very similar to that used for flash welding. It can be used only if the parts to be welded are equal in cross-sectional area. The abutting surfaces must be prepared very carefully to provide for proper heating. The difference from flash welding is that the parts are clamped in the welding machine and force is applied, bringing them tightly together. High-amperage current is then passed through the joint, which heats the abutting surfaces. When they have been heated to a suitable forging temperature, an upsetting force is applied and the current is stopped. The high temperature of the work at the abutting surfaces, plus the high pressure, causes coalescence to take place. After cooling, the force is

FIGURE 8-22 Upset welding process.



released and the weld is completed. There is no arc or flash in upset welding. The area at the joint is usually enlarged over its original dimension. This process is used for welding small wires, tubing, piping, rings, strips, and so on, where the cross-sectional areas of both pieces are identical. If intimate contact is not obtained because of improper joint preparation, the weld will be defective.

Percussion Welding

"Percussion welding (PEW): a welding process that uses an arc produced by a rapid discharge of electrical energy. Pressure is applied percussively during or immediately following the electrical discharge." This process is quite similar to flash welding and upset welding, but is limited to parts of the same geometry and cross section. It is more complex than the other two processes, in that heat is obtained from an arc produced at the abutting surfaces by the very rapid discharge of stored electrical energy across a rapidly decreasing air gap. This is immediately followed by application of pressure, providing an impact that brings the two parts together in a progressive percussive manner. The advantage of the process is that there is an extremely shallow depth of heating and the time cycle is very short. It is used only for parts with fairly small cross-sectional areas. It can be used for welding a large number of dissimilar metals. It is used for very specialized applications and the process is entirely automatic.

High-Frequency Resistance Welding

"High-frequency resistance welding: a group of resistance welding process variations that use high-frequency welding current to concentrate the welding heat at the desired location." There are two primary variations.

High-frequency seam welding (RSEW-HF) is a resistance seam welding process variation in which high-frequency welding current is supplied through electrodes into the workpieces. *High-frequency upset welding* (UW-HF) is an upset welding process variation in which high-frequency welding current is supplied through electrodes into the workpieces (Figure 8-23). The systems are very similar except that in one case the induction work coil generates the heat in the workpieces, and in the other case sliding electrodes are in contact with the workpieces. The frequency ranges from 10 to 500 kHz. The upsetting force is applied by rollers. These variations are ideally suited for making pipe, tubing, structural shapes, and other formed items made from continuous strip. In this process the high-frequency welding current is introduced into the metal at the surfaces to be welded but prior to their contact with each other. Current is introduced by means of sliding contacts at the edge of the joint or by induction coil. The high-frequency welding current flows along one edge of the seam to the welding point between the pressure rolls and back along the opposite edge to the other sliding contact. The current is of such high frequency that it flows along the metal surface to a depth of several thousandths of an inch. Each edge of the joint is the conductor of the current and the heating is concentrated on the surface of these edges. At the area between the closing rolls the material is at the plastic temperature, and with the pressure applied, coalescence occurs. The surfaces must be reasonably true with respect to each other, and clean. No other special preparation is required. The process can be used to join most common metals and certain dissimilar metals. The process is entirely automatic and utilizes special control equipment. It is possible to make welds at extremely high speeds, approaching 500 ft/min (150 m/min) for thin-wall tubing.

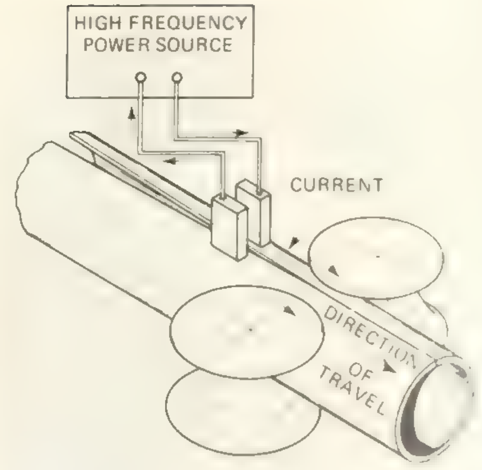


FIGURE 8-23 High-frequency resistance welding.

A variation of the high-frequency process is called melt welding. It involves applying high-frequency current to the joint. The current flowing between the two contacts heats and melts the area between them. The melted metal flow together and produce a small cast weld. It can be used for making T welds and lap and butt welds.

Resistance Welding Safety

Only resistance welding equipment meeting the Resistance Welding Manufacturing Association (RWMA) standards should be utilized. All equipment must be installed in conformance with the *National Electrical Code* and local requirements.

Operating controls such as start buttons and foot switches must be guarded to prevent accidental startup of equipment. All chains, gears, linkages, belts, and so on, in the machine must be guarded in accordance with American National Safety Standards.

Fixed single-point equipment or single-ram equipment should be guarded or require two start buttons so that the operator's hands cannot be in the point of welding during operation. On multiple-point equipment, interlocks, latches, barriers, or guards should be used. For

portable equipment two handles are required so that the operator's fingers cannot be in the contact area.

All electrical controls must be enclosed in approved cabinets that should be grounded to earth. Stop buttons should be available at the operator's station to absolutely stop the welding sequence when they are pushed. If capacitors are involved in the welding machine, they should be properly enclosed and a positive device should be installed to discharge all capacitors whenever the enclosure is open.

Operators should wear face shields, spectacles, or goggles, depending on the type of work. Such devices are necessary to protect the face and eyes from flying sparks. Operators designated to operate resistance welding equipment must be properly instructed and judged competent to operate the equipment.

8-2 ELECTRON BEAM WELDING

"Electron beam welding (EBW): a welding process that produces coalescence of metals with the heat obtained from a concentrated beam, composed primarily of high-velocity electrons, impinging on the joint. The process is used without shielding gas and without the application of pressure." It is a fusion welding process with the melting together of base metal, and possibly of filler metal, to produce a weld. Heat is generated in the workpiece as it is bombarded by the high-velocity electron beam. The kinetic energy, energy of motion, of the electrons is transferred to heat upon impact. It is a highly concentrated, high-powered source of heat and it acts similar to the arc of gas tungsten arc welding or the plasma of plasma arc welding in making welds.

The electron beam welding process was developed in the 1950s in the atomic energy industry.[4] The nuclear industry had need to weld refractory and reactive metals. The first successes were made by the French atomic energy industry, followed by the Americans. Soon after, German scientists developed their own version of electron beam welding. Since the 1960s, commercial equipment has been available and has been improved continuously. Electron beam welding is now a popular process that is growing.

Principles of Operation

The original work was done under a high vacuum using an electron gun similar to an x-ray tube. In an x-ray tube the beam of electrons is focused on a target to give off x-rays; the target becomes very hot and requires water cooling. In electron beam welding, the target is the workpiece, which absorbs the heat to bring it to the molten stage to allow welding.

A modern electron beam welding machine consists of at least the following:

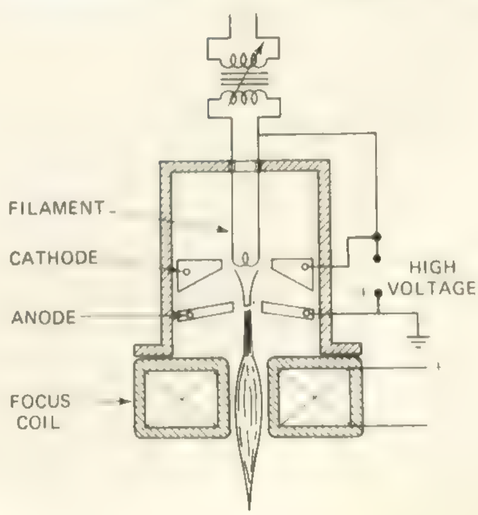
- Electron beam gun
- Power supply and control
- Gun and work motion equipment
- Welding chamber, with vacuum pumps
- Alignment and viewing system
- Miscellaneous auxiliary equipment

The electron beam gun is a device for producing and accelerating electrons. It consists of an emitter called the filament or cathode, a grid cup, an anode, and focusing and deflection coils. It is housed in a hard vacuum. When the focus and deflection coils are included, this is called an electron beam gun column (Figure 8-24). The entire electron beam gun column is exhausted to a vacuum of 0.1 to 0.01 μm or 0.0001 torr (10^{-4} torr). One torr equals one millimeter of mercury. Atmospheric pressure is 760 torr or 760 mm hg, which is also 14.7 psi.

The emitter is either a tungsten filament or a tungsten rod heated by a filament. Electrons are freed from the tungsten when it is heated to a high temperature, causing thermionic emission. Electrons freed from the cathode or emitter are attracted to the anode, which is the positive pole. The beam is collected and partially focused and attracted to the anode, which has a hole. Beyond the anode hole, the beam is focused by means of magnetic forces generated by the focusing coil. Following this, the beam may be deflected by magnetic fields generated by deflection coils. The beam then leaves the electron beam gun through an exit port and impinges on the workpiece.

The next major component is the power supply and control. This unit takes power from the utility line and provides the beam current, normally less than 1 A, and the acceleration voltage, which is thousands of volts. The beam power is the product of the beam current and the

FIGURE 8-24 Electron beam welding process.



acceleration voltage measured in kilowatts, and ranges from a few kilowatts up through 50 kW. The control system has total control of the electron beam welder system. It also controls relative motion between the gun and workpiece. It powers the vacuum pumps and other devices. Controls for electron beam welding machines must be very precise and are often computer driven. In many installations the electron gun is fixed and can be adjusted for specific targets. The work-handling equipment used to move the workpiece can be quite complex, ranging from single-axis motion to five or more axes of motion in three planes and with rotary motion. Equipment of extreme precision must be used. The travel mechanism must be designed for vacuum installations since lubricants and certain insulating varnishes in electric motors may volatilize in a vacuum. In some cases, motors and gearboxes are located outside the vacuum chamber, with shafts operating through pressure-sealed bearings.

The next major component is the welding chamber, which must be absolutely airtight. This container, which is evacuated to reduce the pressure to a high vacuum, must be extremely strong so that it will not crush under atmospheric pressure. It requires openings to allow the work to be enclosed and removed. The openings, doors, and so on, must be sealed to a vacuum tightness. The work chamber must be sufficiently large to enclose the parts to be welded, but should not be overly large because of the time and expense of evacuating it. Early chambers utilized a hard vacuum—the same as the vacuum in the electron beam gun column. As electron beam guns became more powerful, a second method of electron beam welding was developed. This allowed welding in a soft vacuum with a pressure of 0.1 torr (10^{-1} torr), known as soft-vacuum electron beam welding. This made larger work chambers possible, with quicker pump-down time.

The third method of electron beam welding, done in the open air, is known as nonvacuum electron beam welding. The electron beam gun is housed in the hard-vacuum chamber and there are several intermediate reduced-pressure chambers between the gun and the work. Each intermediate chamber has a reduced pressure with very small holes from one chamber to another so that the electron beam passes through, but too small for a volume of air to pass. This mode of operation eliminates the vacuum chamber for the work; however, certain sacrifices are made. Vacuum pumps are required to eliminate air in the electron beam gun column, in the work chamber, and in any intermediate chambers between them. Two vacuum pumps are required to produce a hard vacuum. A mechanical pump is used to eliminate the large volume of air and will pull a vacuum in the 10^{-1} torr range. To obtain the hard vacuum, a diffusion pump is required. The diffusion pumping does not remove large volumes of air and takes considerable time to reach a hard vacuum. The pumps are operated automatically by the control system.

The last component is an optical viewing system to line up the electron beam with the weld joint. This must be very accurate since the welding beam is so small. The optical system is connected to the work motion device for precise alignment. Figure 8-25 shows a typical low-powered electron beam welding machine. Figure 8-26 shows a higher-powered machine with a larger work chamber.

Electron Beam Welding Equipment

There is a wide selection of electron beam welding machines, based on:

- The operating pressure of the work chamber
- The acceleration voltage
- The beam power level
- The complexity of control system

Electrons in the beam collide with molecules in air and lose velocity and direction. This causes scattering and dissipation of the beam strength. The hard-vacuum mode provides the most efficient welding operation. In the hard-vacuum mode the stand-off distance (the distance from the exit of the electron beam to the workpiece) can be as far as 30 in. (660 mm), and material up to 6 in (150 mm) thick can be welded. Travel speeds will be the highest. On the negative side, the pump-down time is fairly long, based on chamber size, and the entire machine is expensive.

In the soft vacuum, sometimes called medium or partial vacuum, the pump-down time is greatly reduced and can be attained by using mechanical pumps without the diffusion pump. Even so, the electron beam gun column must be at a hard vacuum. With the soft vacuum, interlock doors can be used so that material can be introduced and taken out while the welding operation continues. Chambers can be larger. However, there is a sacrifice in operating conditions; the stand-off distance is reduced by approximately one-half, thickness is reduced to 2 in., and speed is also reduced with the same power.

In the nonvacuum mode, sometimes called out-of-vacuum or welding in the air, the workpiece is at atmosphere pressure. The stand-off distance is reduced to 1½ in. (37 mm), the maximum thickness is 2 in. (50 mm), and speed is reduced, again using the same power. A nonvacuum system requires a container to shield people from potential radiation. The size of work is unlimited and work motion is easier since the components are in the air. Even with the nonvacuum system, a hard vacuum is required for the electron beam gun, and intermediate reduced-pressure chambers are also required. Figure 8-27

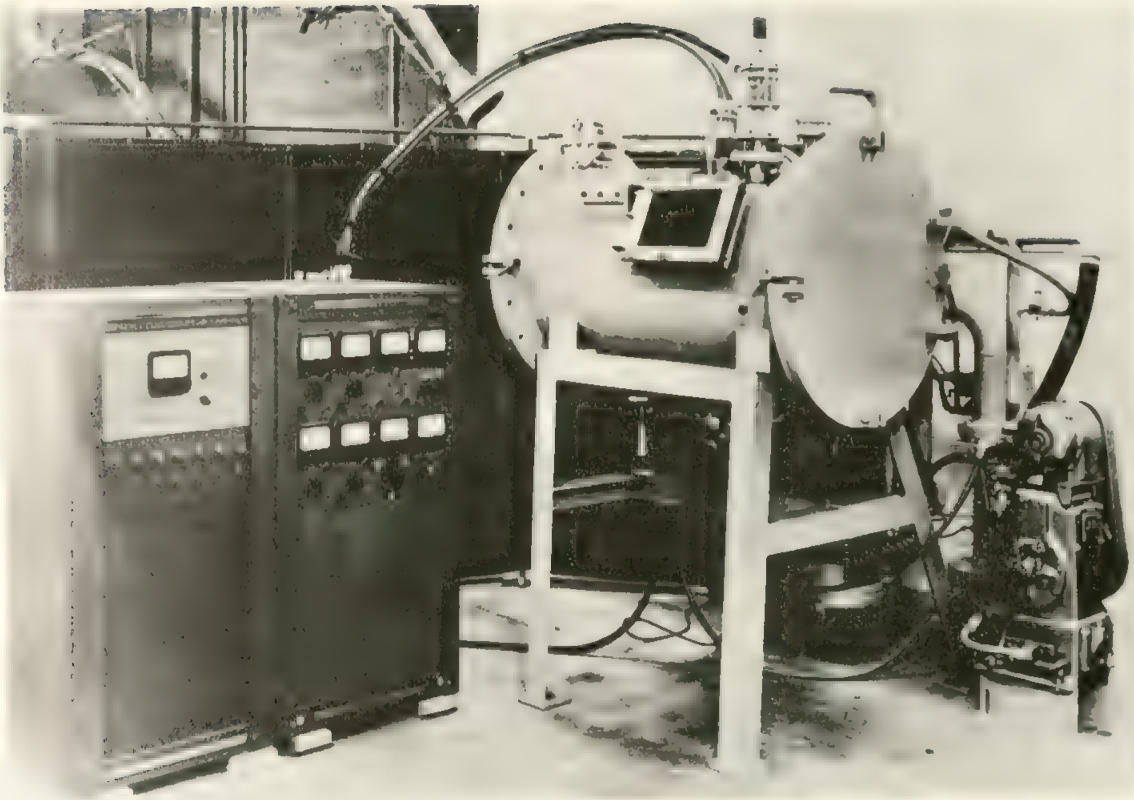


FIGURE 8-25 Electron beam low-power welding equipment.

FIGURE 8-26 Electron beam high-power welding equipment.

FIGURE 8-27 Electron beam welding catalytic converters in air.

shows electron beam welding of catalytic converters in the air.

There is a new method used experimentally which allows the welding to be done in a soft vacuum, which is contained in a small chamber attached to the work by means of seals. This allows the welding gun to move but requires that a seal be maintained between the welding apparatus and the workpiece. For some applications this is possible; for others it is not.

The acceleration voltage is another way of specifying electron beam welding machines. There are low-voltage machines having an output of 15 to 60 kV, and high-voltage machines with an output of 100 to 200 kV. It is difficult to compare equipment on the basis of the accelerating voltage only since the basic design of the low- and high-voltage systems are radically different. From a safety standpoint, an accelerating voltage of less than 20 kV produces soft x-rays, while an accelerating voltage of over 20 kV produces hard x-rays. Shielding is more demanding against radiation as the acceleration voltage increases. The lower-voltage machines operate at a higher current; typically, 30- to 60-kV machines operate at a 500-mA beam current. The high-voltage machines of 150 kV operate at 40 mA. The higher-voltage machines produce a greater depth-to-width ratio of the weld nugget. This could be the difference between a 12:1 depth-to-width ratio versus a 25:1 depth-to-width ratio. The higher-voltage machines can utilize a longer stand-off distance than can low-voltage machines; however, low-voltage machines are simpler in construction and less maintenance is required.

Electron beam machines are rated by their output power in kilowatts. They are available from approximately 1 kW to as high as 40 kW.

The ability of a machine to do work is based on its beam power, which is the product of the beam current and the accelerating voltage in kilovolts. Beam power relates to the power density of the electron beam. Power densities in the range 100,000 to 10,000,000 W per square inch can be obtained. Temperatures are in the neighborhood of 25,000°F, which causes practically instantaneous vaporization of the surface of the workpiece. The depth of penetration is generally considered a function of the accelerating voltage. The accelerating voltage relates to the speed at which the electrons travel. The beam current, which relates to the number of electrons in the beam, influences the weld configuration.

The major advantage of electron beam welding is its tremendous penetration, which occurs when the highly accelerated electron hits the base metal. It will penetrate slightly below the surface and at that point release the bulk of its kinetic energy, which turns to heat energy. This brings about a tremendous temperature increase at the point of impact. The succession of electrons striking the same place causes melting and then evaporation of the base metal. This creates metal vapors, but the electron beam travels through the vapor much easier than solid metal. This causes the beam to penetrate deeper. The depth-to-width ratio can exceed 20:1. As the power density is increased, penetration is increased. An electron beam weld and a gas tungsten arc weld are compared in Figure 8-28.

The heat input of electron beam welding is controlled by four variables: (1) the number of electrons per second hitting the workpiece or beam current; (2) the electron speed at the moment of impact, the accelerating

FIGURE 8-28 Gas tungsten arc and electron beam weld.

potential; (3) the diameter of the beam at or within the workpiece, the beam spot size; and (4) the speed of travel, the welding speed. The first two variables, beam current and accelerating potential, are used in establishing welding parameters. The third factor, the beam spot size, is related to the focus of the beam, and the fourth factor is also part of the procedure. Normally, the electron beam current ranges from 250 to 1000 mA; the beam currents can be as low as 25 mA. The accelerating voltage is within the two ranges mentioned previously. Travel speed can be extremely high and relates to the thickness of the base metal. The other parameter that must be controlled is the gun-to-work distance. It is difficult to establish welding schedules for electron beam welding because of the number of variables involved. However, Figure 8-29 shows the relationship between travel speed and depth of penetration.[5]

The beam spot size can be varied by the location of the focal point with respect to the surface of the work. Penetration can be increased by placing the focal point below the surface of the workpiece. As it is increased in depth below the surface, deeper penetration will result. When the beam is focused at the surface, there will be more reinforcement on the surface. When the beam is focused above the surface, there will be excessive reinforcement and the width of the weld will be greater.

Penetration is also dependent on the beam current. As beam current is increased, penetration is increased. The other variable, travel speed, also affects penetration. As travel speed is increased, penetration is reduced.

The power in an electron beam weld would be in the same relative amount as for a gas metal arc weld. The gas metal arc weld would require higher power to produce the same depth of penetration. The energy in joules per inch for the electron beam weld may be only one-tenth as great as the gas metal arc weld. The electron beam weld will be equivalent to the SMAW weld, with less power because of the tremendous penetration obtainable by electron beam welding. The power density is in the range 100 to 10,000 kW/in.[2]

Since the electron beam has tremendous penetrating characteristics, with the lower heat input, the heat-affected zone is much smaller than that of any arc welding process. In addition, because of the almost parallel sides of the weld nugget, distortion is greatly minimized. The cooling rate is much higher, and for many metals this is advantageous; however, for high-carbon steel this is a disadvantage and cracking may occur.

Some weld joint details for electron beam welding are shown in Figure 8-30. Welds are extremely narrow, and therefore preparation for welding must be extremely accurate.[6] The width of a weld in ½-in. (12-mm)-thick stainless steel, for example, would only be 0.04 in. (0.10 mm), and for this reason small misalignment would allow the electron beam to miss the joint completely. Special optical systems are used which enable the operator

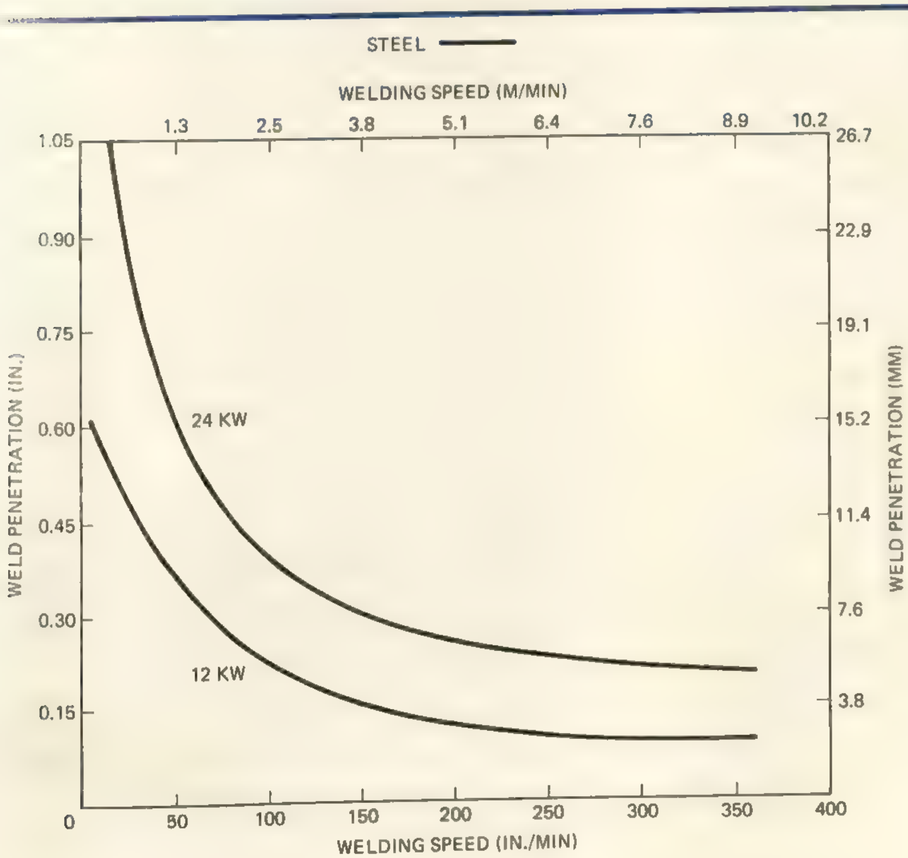


FIGURE 8-29 Travel speed versus penetration. (From Ref. 5.)

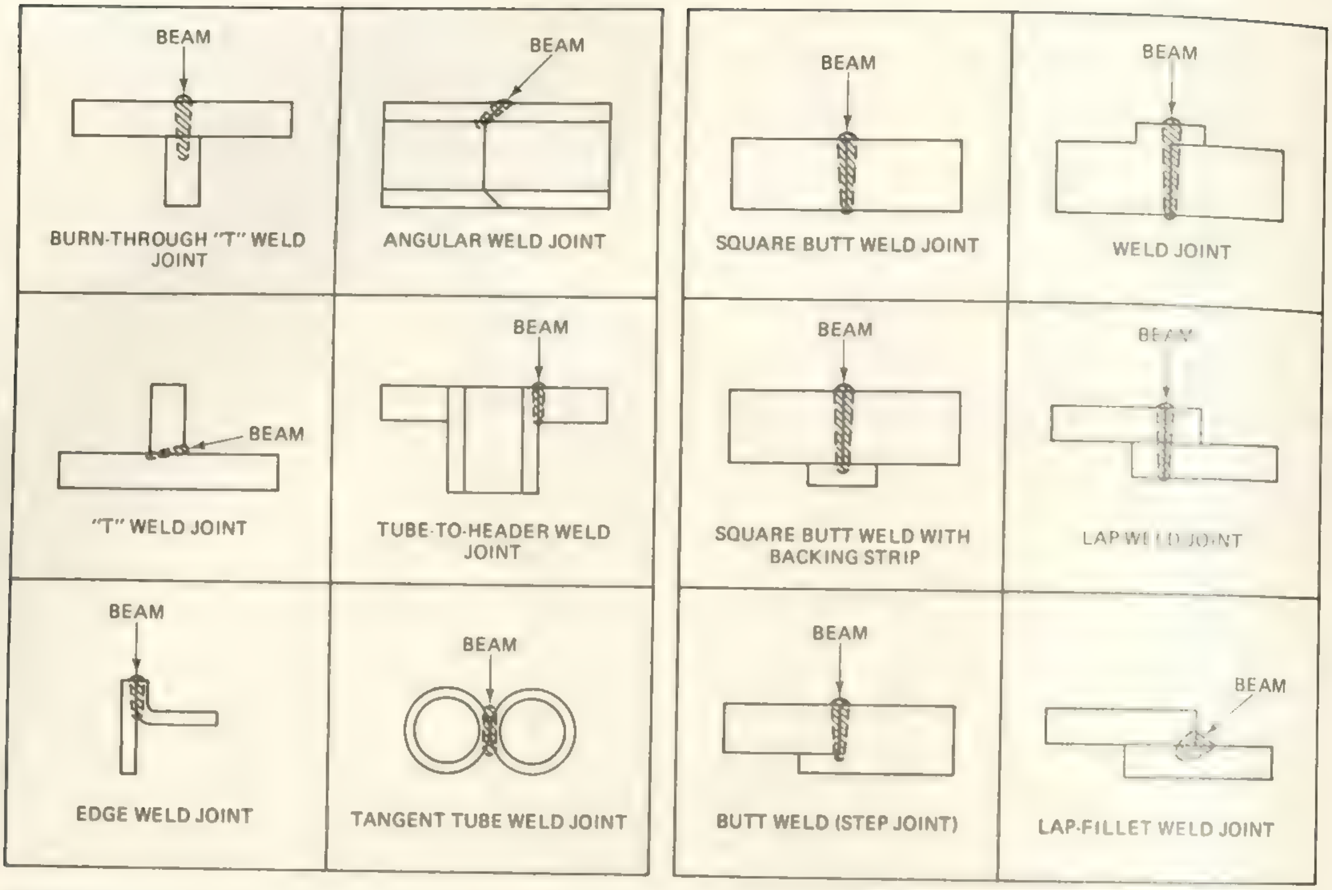


FIGURE 8-30 Weld joint types for EBW.

to align the work with the electron beam. The electron beam is not visible in the vacuum. The depth-to-width ratio allows for special lap-type joints. Where joint fitup is not precise, ordinary lap joints are used and the weld is an arc seam weld. Normally, filler metal is not used in electron beam welding; however, when welding mild steel, highly deoxidized filler metal is sometimes used to deoxidize the molten metal and produce dense welds.

Almost all metals can be welded with the electron beam welding process. The metals that are most often welded are the super-alloys, the refractory metals, the reactive metals, and the stainless steels. Many combinations of dissimilar metals can also be welded.

One of the disadvantages of the electron beam process is its high capital cost. The price of the equipment is very high, and it is expensive to operate, due to the need for vacuum pumps. In addition, fitup must be precise and locating the parts with respect to the beam must be perfect.

Electron beam welding is not a cure-all; there are still the possibilities of defects of welds. A major problem is welding plain carbon steel in a vacuum. The melting of the metal releases gases originally in the metal and results in a porous weld. If deoxidizers cannot be used, the process is not suitable. It is expected that the electron beam process will become more popular for welding specialized metals where critical quality standards must be met.

Electron Beam Cutting

Electron beam cutting (EBC) is a thermal cutting process that severs metals by melting them with the heat from a concentrated beam composed primarily of high-velocity electrons impinging on the workpiece. The difference between electron beam welding and cutting is the heat input–heat output relationship. The electron beam generates heat in the base metal, which vaporizes the metal and allows it to penetrate deeper until the depth of the penetration, based on the power input, is achieved. In welding the electron beam actually produces a hole, known as a *keyhole*. The metal flows around the keyhole and fills in behind. In the case of cutting, the heat input is increased so that the keyhole does not close.

All the metals that can be welded can also be cut. The quality of the cut surface is equal to the quality of a good oxyacetylene machine cut. The ability to shape cut is limited only by the ability to move the work or the electron gun. The problems of electron beam cutting are greater than those of welding. The work must be in a

vacuum. A large amount of volatilized metal will tend to plate out on the inside of the vacuum chamber. In view of these difficulties, the laser beam is replacing the electron beam for cutting.

8-3 LASER BEAM WELDING

Laser beam welding (LBW) is a welding process that uses the heat from a laser beam impinging on the joint. The process is used without a shielding gas and without the application of pressure. The laser is a device that produces a concentrated coherent light beam by stimulating electronic or molecular transitions to lower energy levels. The word *laser* is an acronym for "light amplification by stimulated emission of radiation." The laser beam is a highly concentrated source of energy which has many applications. It can be used for welding, for cutting metals and nonmetals, for surface heat treating of metals, and for cladding by fusing powders to base materials. It can also be used for brazing and soldering, and for drilling, machining, and marking. It is also used in other fields: medicine, communications, marking, and surveying.

The laser was conceived by Townes[7] in 1951. In May 1960, T. H. Maiman of Hughes Aircraft Research Laboratories in California demonstrated a device, working in the visible region of the spectrum, utilizing a synthetic ruby crystal excited by a gas discharge flash tube and emitting short pulses of red coherent light.[8] In 1961, Javan of Bell Labs produced a laser beam from a mixture of helium and neon gases excited directly by an electrical discharge. The CO_2 laser developed in 1964 by Patel of Bell Labs has become the industrial workhorse.[9]

Since its development the laser has found many applications in communication, surveying, medicine, and metalworking. The focused laser beam has a very high energy concentration, on the same order as an electron beam in a hard vacuum. It is a source of electromagnetic energy, or light, that can be projected without diverging and can be concentrated to a very small spot. The beam is coherent and monochromatic (i.e., a single wavelength). It is produced by a lasing medium, which is the source of photons.

Light from an incandescent electric light bulb is "incoherent," which means out of phase, and as a result has a high divergence or is radiated in all directions from the source. It is not monochromatic, which means that it contains a wide spectrum of wavelengths (colors), from short to long. The radiation from a laser is monochromatic, which provides for a single wavelength, which in turn allows for minimum beam divergence. The beam is also coherent, in that the light is all in phase. The laser beam has a high energy content; thus when it impinges on a surface, it creates heat. This heat can be used exactly as heat produced by an electron beam or welding arc.

Laser Types

There are two basic types of lasers used in metal working. The original types are the solid-state lasers, which use a solid medium. The second type are the gas lasers, which normally use a mixture of helium, nitrogen, and CO_2 gas in a tube. In either case, when the medium is sufficiently excited, it emits photons, which become the laser beam.

There are three basic types of solid-state lasers in commercial use: (1) the ruby laser, which uses a synthetic ruby with chromium in aluminum oxide; (2) the Nd:glass laser, which uses neodymium in glass; and (3) the Nd:YAG laser, which uses a crystal of yttrium aluminum garnet doped with neodymium. In solid-state lasers, the Nd ions emit photons when their electrons are excited and then allowed to drop back to their original energy state.

The wavelength of the laser beam produced by solid-state lasers is 0.694 μm for the ruby laser and is 1.06 μm for Nd:glass or Nd:YAG lasers. A laser beam of this short a wavelength is extremely dangerous to humans. Therefore, eye protection is required, using laser beam–absorbing goggles.

The beam operating mode for the ruby laser and the Nd:glass laser is usually pulsed. The Nd:YAG laser can operate in the continuous-wave mode or the pulsed mode. The average output power ranges from 10 to 20 W for a ruby laser, and up to 600 W for the YAG lasers. The beam diameter ranges from 1/16 in. (1.6 mm) minimum to ½ in. (25 mm) for the ruby laser, from ⅛ in. (3 mm) to ½ in. (25 mm) for the Nd:glass, and from 0.040 in. (1 mm) to ⅜ in. (10 mm) for the Nd:YAG, depending on whether it is continuous wave or pulsed.

The solid-state ruby laser utilizes a single crystal of ruby made into a rod approximately 1 in. (25 mm) in diameter and approximately 12 in. (300 mm) long. The end surfaces of the rod are ground flat and parallel and are polished to extreme smoothness. Both flat ends are covered with silver to reflect light; however, a small area in one end is left uncovered to allow the laser beam to exit from the rod. The ruby rod is closely surrounded by the high-intensity light source, which is a flash tube with a xenon or krypton element. Figure 8-31 is a simplified diagram of a solid-state beam source. When the tube is flashed, it emits an intense pulse of light which lasts for approximately 2 milliseconds. The high-intensity beam of coherent red light is emitted from the opening in the silver reflector on one end of the ruby rod. A burst of laser beam light, which lasts about 2 milliseconds, occurs each time the flash tube is flashed. It is not possible to flash the ruby too fast or too often because of heat generated in the ruby crystal and in the flash tube. Thus it cannot operate continuously because of the heat build-up. The flash period or pulse durations are very short and there is a relatively long period between pulses. The

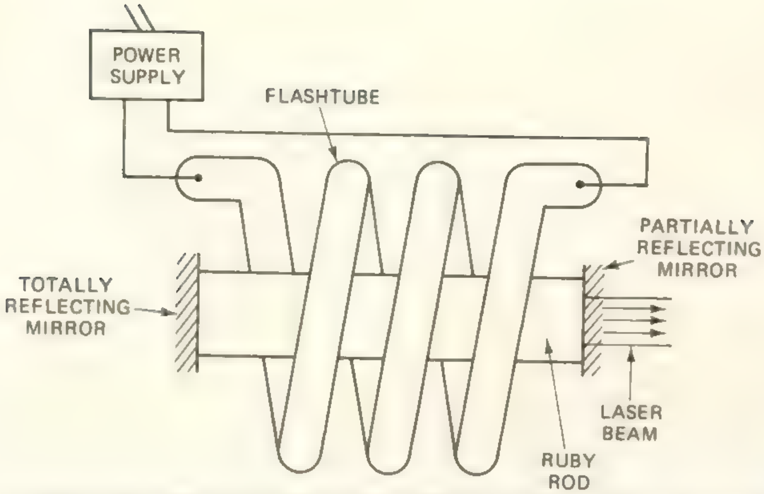


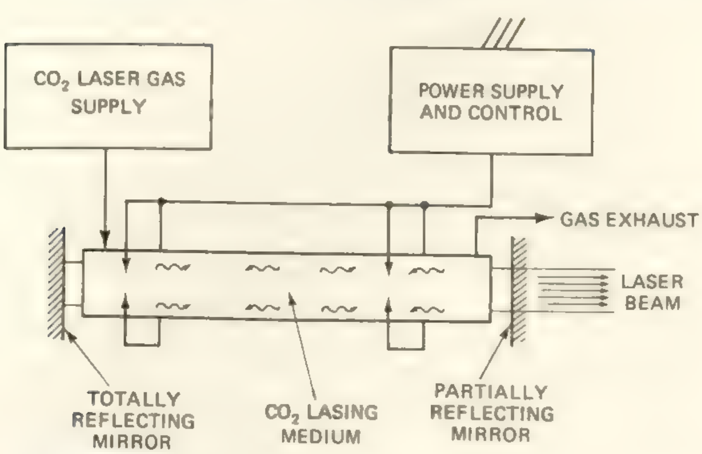
FIGURE 8-31 Pulsed-ruby laser.

other two solid-state lasers operate in the same manner.

The CO_2 laser is widely used for metalworking. The carbon dioxide laser uses gas that is a mixture of CO_2, helium, and nitrogen. Excitation of the gas laser is by means of high-voltage, low-current electric power. The electrical discharge excites the CO_2 molecules, which on returning to their original energy state, emit photons. Mirrors are placed on both ends of the tube, one entirely reflective and the other with small partially transmissive area to allow the beam to exit. This forms a cavity in which photons build up. The freed photons travel between the mirrors and excite the CO_2 molecules, starting a chain reaction of photon emissions. A stream of photons, the laser beam, exits through the unsilvered section of the one mirror. The wavelength of the laser beam is 10.6 μm. This wavelength is longer and does not have the safety problems of the short-wavelength beam. The CO_2 gas lasers can be operated in the continuous-wave mode or in the pulsed mode. A gas laser beam source is shown in Figure 8-32.

There are several types of CO_2 lasers. The early or lower-powered type used a "sealed tube" which has a

FIGURE 8-32 Basic CO_2 laser system.



power output of from 3 to 100 W. The axial-flow type, which is a more complex method of producing laser beams, will produce from 50 W to 2 kW average output power. Another type, known as the transverse-flow type, has an average output power of from 2 to 15 kW. The laser power supply system is called an oscillator.

These different types of CO_2 lasers involve different designs of the beam-producing apparatus. The size of the apparatus and the efficiency of the system are different.

A summary of laser types and outputs is shown in Figure 8-33. There are two operating modes for lasers. One is called the continuous-wave mode, and the other, the pulsing mode. These are similar to the operating modes of other welding processes.

Laser Beam Welding

The laser beam is very intense and unidirectional but can be focused and reflected in the same way as an ordinary light beam. The focus size is controlled by the choice of lenses and mirrors and the distance to the workpiece. The spot size can be made as small as 0.40 in. (1 mm) to up to ½ in. (25 mm). The smaller focus spot size is used for cutting and welding, and the larger spot size is used for heat treating. The laser beam can be used in open air and can be transmitted long distances with only minimal loss of power.

A block diagram of a laser beam welding system is shown in Figure 8-34. This shows the major components: the laser beam source (sometimes called the oscillator), the power supply, the cooling system, the gas supply for the laser beam source, the beam delivery system, the beam output coupling to the workpiece, the motion system for moving either the beam or the workpiece or both, the control system for the beam source and motion system and auxiliary systems, and the real-time monitor or feedback systems. Workpiece motion, parts handling, and workpiece motion feedback or monitoring are similar to those of other automatic welding

Use Factors	Laser Type			
	Solid-State Type			Gas Type
	Ruby	Nd:YAG (CW)	Nd:YAG (Pulsed)	CO_2
Wavelength (μm)	0.694	1.06	1.06	10.6
Continuous wave (CV)	No	No	No	Yes
Pulsed mode	Yes	No	Yes	Yes
Average power (W)	10–20	0.04–600	0.04–600	50–25,000
Beam diameter (mm)	1.5–25	1–6	5–10	1–10
Beam diameter (in.)	0.058–0.975	0.040–0.235	0.195–0.390	0.040–0.390
Use for welding	Yes	No	Yes	Yes
Use for cutting	No	Yes	Yes	Yes

FIGURE 8-33 **Summary of laser types for metalworking.**

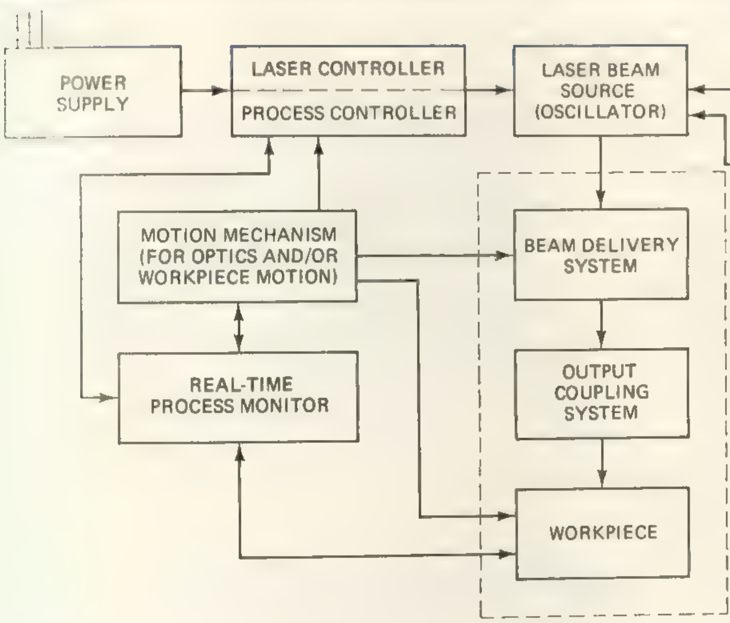


FIGURE 8-34 **Block diagram of CO_2 laser system.**

systems, except that the accuracy of movement must be very precise.[10] The beam source power supply, cooling system, gas supply, and control system are particular to laser systems and are based on the types of laser, either solid state or gas, and the mode of operation, continuous or pulsed.

The beam delivery system must match the type of laser used. Robots can be used for manipulating the beam. Fiber optics are used to transmit the laser beam from a Nd:YAG laser. However, Nd:YAG lasers have a power of only 600 W. For higher-power lasers, lenses and mirrors are used. Six-axis robots can be fitted with an articulated system so that they can deliver a high-powered CO_2 laser beam. The coupling system must match the type of laser used and the particular application.

When using a laser beam for welding, the beam impinges on the surface of the base metal with such a concentration of energy that the surface is melted and volatilized. When the metal is raised to its melting temperature, the surface conditions have a minor effect on reflecting the beam.

The distance from the optical cavity to the workpiece has little effect on the laser. This is because it can be focused to the proper spot size at the work, with the same amount of energy available whether it is close or far away.

With laser welding the molten metal takes on a radial configuration similar to plasma arc welding, known as "melt-in" welding. When the power density rises above a certain threshold level, keyholing occurs, the same as with plasma arc or electron beam welding. Keyholing provides for extremely deep penetration, which gives the weld a high depth-to-width ratio. Keyholing also minimizes the

problem of beam reflection from the shiny molten metal surface since the keyhole behaves like a black body and absorbs the majority of the energy. For some applications, inert gas is used to shield the molten metal from the atmosphere. The metal vapor in the weld area may cause a breakdown of the shielding gas and create a plasma in the region of high beam intensity just above the work surface. The plasma absorbs energy from the laser beam and can actually block the beam and reduce melting. This is overcome by using an inert-gas jet directed along the metal surface, which eliminates the plasma buildup. It also shields the weld from the atmosphere.

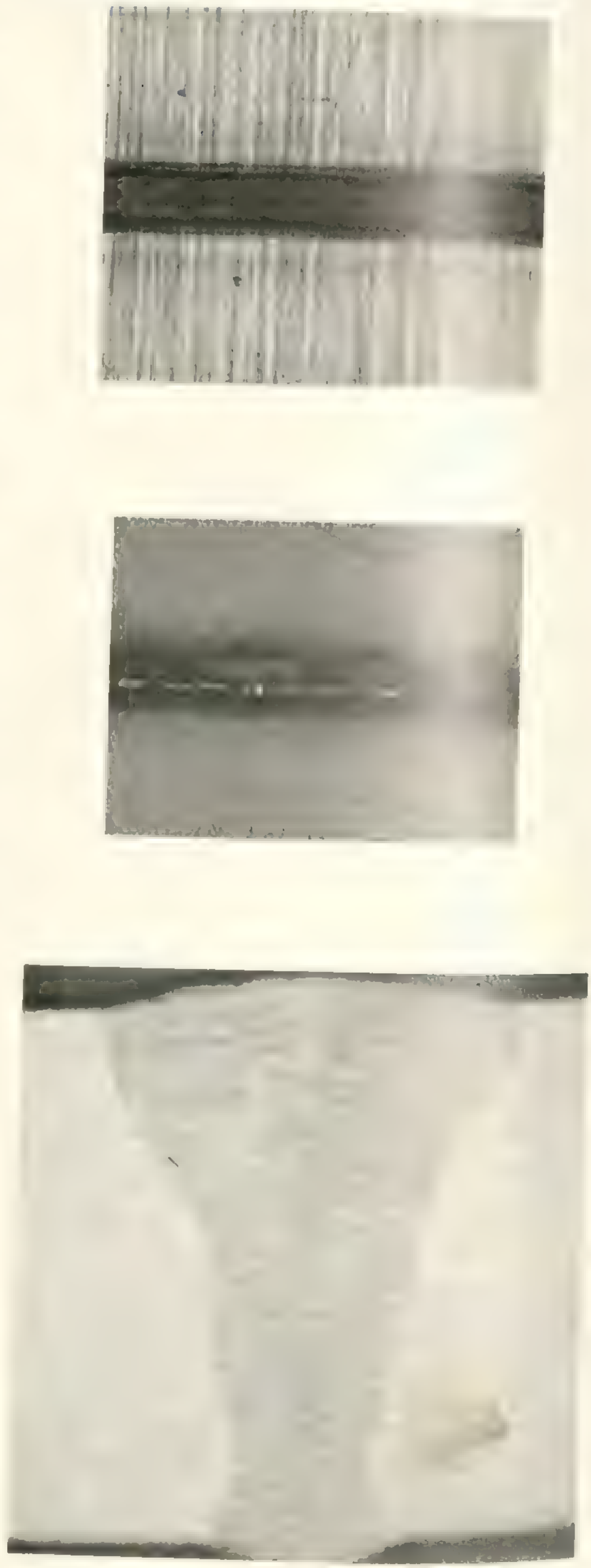


FIGURE 8-35 Welds made in stainless steel.

The welding characteristics of the laser are similar to those of the electron beam. The laser can weld the same joint types. The concentration of energy by both beams is similar, with the laser having a power density on the order of 10^6 W per square centimeter. The power density of the electron beam is slightly greater.

The location of the focal point of the beam with respect to the surface of the workpiece is important. Maximum penetration occurs when the beam is focused slightly below the surface. Penetration is less when the beam is focused on the surface or deep within the surface. As power is increased, the depth of penetration increases.

Laser beam welding produces a tremendous temperature differential between the molten metal and the base metal immediately adjacent to the weld. Heating and cooling rates are much higher in laser beam welding than in arc welding, and the heat-affected zones are much smaller. Rapid cooling rates can create problems, such as cracking in high-carbon steels.

The laser beam has been used to weld carbon steels, high-strength low-alloy steels, aluminum, stainless steel, and titanium. Laser welds are similar in quality to welds made by the electron beam process. Filler metal is used to weld metals that tend to show porosity when welded with either EB or LB welding.

Materials ½ in. (12 mm) thick are being welded at a speed of 10 in. (250 mm) per minute. Figure 8-35 shows the top, underside bead, and the cross section of a laser weld made on stainless steel. This illustrates the characteristic cross section and the depth-to-width ratio of a laser weld. The welding speed for stainless steel of different thicknesses[11] welded with different-size power CO_2 laser welding machines is shown in Figure 8-36.

The efficiency of laser beam welding equipment is 5 to 10%, but as new equipment becomes available this will increase. The cost of the equipment will decrease in the future. More welding applications for laser welding are being found daily, and its use will increase.

Laser Beam Cutting

Laser beam cutting (LBC) is a thermal cutting process that severs material by locally melting or vaporizing with

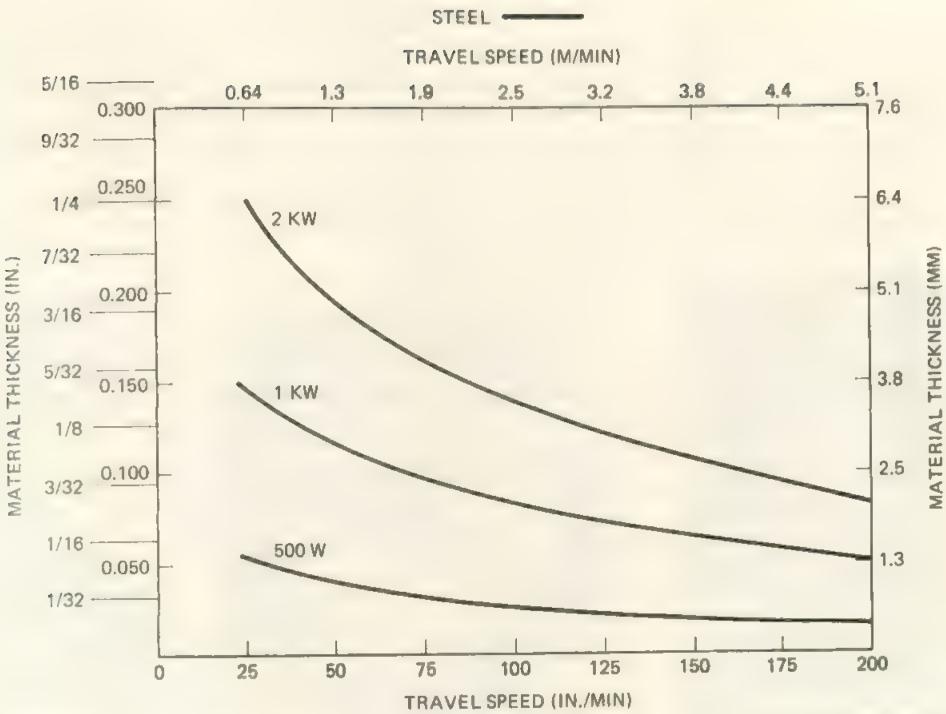


FIGURE 8-36 Laser welding speeds.

the heat from a laser beam. The process is used with or without gas jets to aid the removal of molten and vaporized material. No gas, air, inert gas, or oxygen can be used.

The concentrated energy in the laser beam is only slightly less than the energy in the electron beam. The ability of both beams to cut materials is essentially the same. Laser beam cutting has many advantages over electron beam cutting. The laser beam can cut metal up to ½ in. thick in the atmosphere. It can be used with automatic shape-cutting equipment at high speeds. The width of the laser beam cut is narrower and the angle of the cut is almost a perfect right angle. The quality of the cut surface is equal or superior to that of the best oxygen-cut surface. The laser beam will cut materials other than metals. It has been used successfully for cutting plastics, wood, cloth, and ceramics. One major use of laser beam is cutting plywood and particleboard in the woodworking industry. Another is to cut cloth for making clothing. In view of this, it has replaced the electron beam for cutting. Figure 8-37 shows the different materials that can be cut with a 400-W CO_2 laser, and the speed of cutting.

For metalworking, machines are available for laser cutting. The more common type uses a gentry frame that spans the workpiece. A typical laser cutting machine is shown in Figure 8-38. The laser head has two axes of motion driven by a CNC controller. Machines of this type are very popular for shape cutting. In some cases the laser head is used in conjunction with a turret punch or shear.

FIGURE 8-37 Cutting speed of different materials. (From Ref. 12.)

Material	Thickness		Cutting Speed	
	mm	in.	m/min	in./min
ABS plastic	4	0.157	4.5	177.1
Acrylic	6	0.236	1.7	66.9
Cardboard	0.1	0.004	96.0	3779.5
Ceramic tile	6.3	0.248	0.3	11.8
Formica	1.6	0.063	7.8	307.1
Plywood	18	0.708	0.5	19.7
Wool suit material	—	—	48.0	1889.7
Galvanized steel	1	0.039	4.5	177.1
High-Carbon steel	3	0.118	1.5	59.0
Mild steel	1	0.039	4.5	177.1
Stainless steel	2.8	0.110	1.2	47.2
Titanium	3	0.188	4.1	161.4

Typical laser-cut parts are shown in Figure 8-39. The dimensional accuracy is better than for oxyfuel gas cutting. The edges of a laser cut are square and sufficiently smooth that additional finishing is not necessary (Figure 8-40).

The power required for laser cutting is relatively low. In general, the continuous-wave CO_2 laser with up to 1 kW power is sufficient to cut thin-gauge metals. The data given in Figure 8-41 show the travel speed of a laser beam for cutting different metals and thicknesses. This

shows two different-size laser machines and uses a jet of oxygen to improve cutting speed.[13] Sharp corners, smooth surfaces, narrow cut width, minimum thermal damage, nonadherent dross, and 90° surfaces are all achieved with laser cutting. The laser beam can be used for drilling holes by using the cutting technique but without travel. Laser beams can also be used for localized surface heat treating, for surfacing, and for fusing sprayed surfaces. Laser applications in metalworking will continue to increase.

FIGURE 8-38 Typical laser shape-cutting machine.

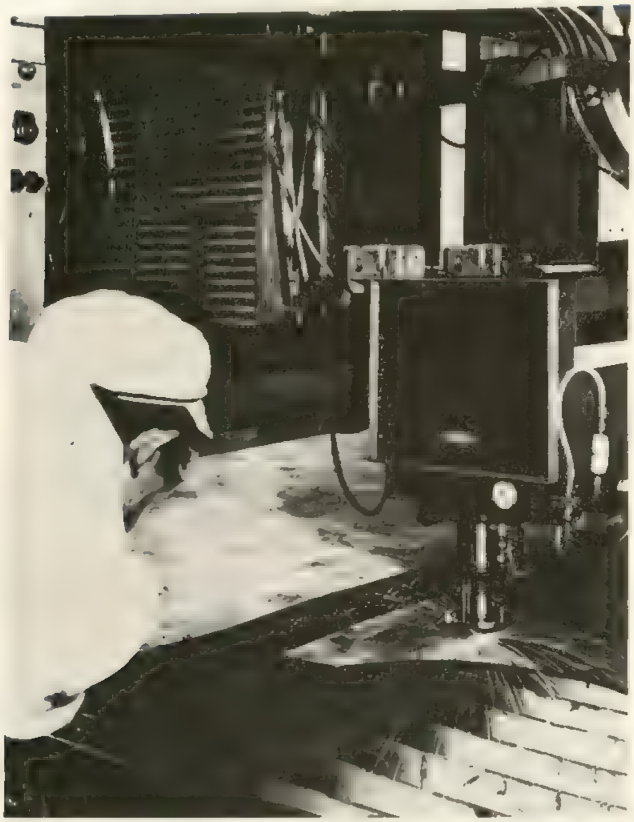
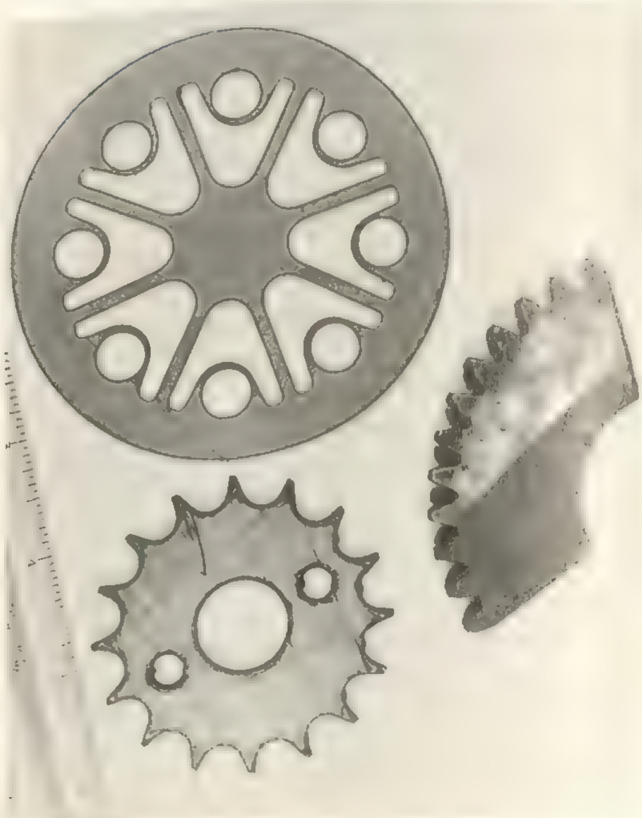


FIGURE 8-39 Typical parts cut by a laser.



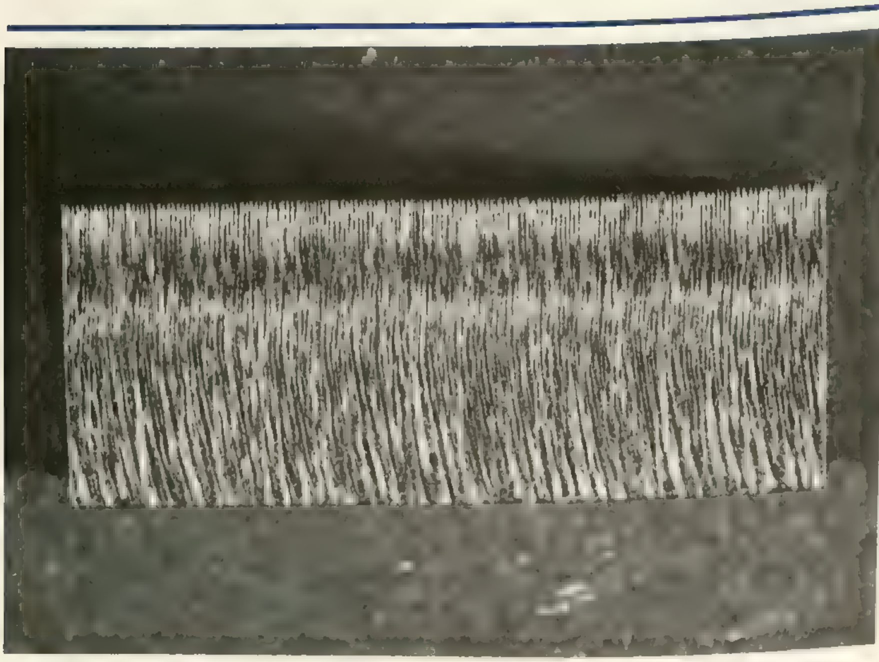


FIGURE 8-40 Surface of cut edges.

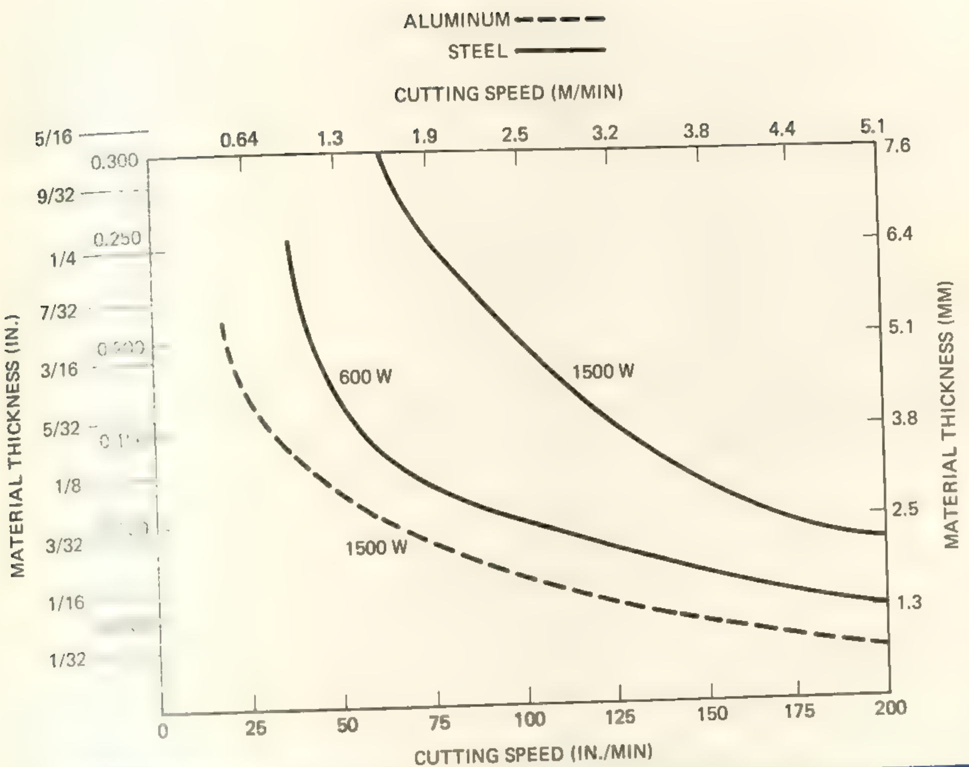


FIGURE 8-41 Cutting speed versus thickness.

QUESTIONS

8-1. What creates the heat in a resistance weld?

8-2. Explain the difference between a resistance spot weld and a projection weld.

8-3. Resistance welding electrodes are usually made of what materials? Why?

8-4. Is filler metal required for making a resistance weld?

8-5. How does seam welding differ from spot welding? Is a resistance seam weld always watertight?

8-6. High-frequency resistance welding is regularly used for making what products?

8-7. What makes flash butt welding different from other resistance welding prcesses?

8-8. What is similar between an electron beam welding machine and a television set? Explain.

8-9. Why is electron beam welding recommended for hard-to-weld metals?

8-10. Explain the difference between electron beam welding in a hard vacuum, a soft vacuum, and in the atmosphere.

8-11. Why is precision joint preparation required for electron beam welding square butt joints?

8-12. What are the advantages and disadvantages of electron beam welding in the air?

8-13. What type of electron beam welding equipment generates x-rays?

8-14. What is the problem with electron beam cutting?

8-15. What does *laser* stand for?

8-16. What safety precautions should be taken when working around lasers?

8-17. Can all laser beams be transmitted by fiber optics?

8-18. What is the advantage of the CO_2 laser?

8-19. Can lasers cut nonmetals? What materials can be cut besides metals?

8-20. What is the advantage of laser welding over electron beam welding?

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9

Welding-Related Processes

OUTLINE

9-1 OXYGEN CUTTING

Oxygen cutting (OC) is a group of thermal cutting processes that sever or remove metal by means of the chemical reaction between oxygen and the base metal at elevated temperatures. The necessary temperature is maintained by the heat from an arc, an oxyfuel gas flame, or other source. In the case of oxidation-resistant metals the reaction is facilitated by the use of a chemical flux or metal power. Five basic processes are involved: (1) oxyfuel gas cutting, (2) metal powder cutting, (3) chemical flux cutting, (4) oxygen lance cutting, and (5) oxygen arc cutting. Each of these processes is different and will be described.

Oxyfuel Gas Cutting

Oxyfuel gas cutting (OFC) is a group of oxygen-cutting processes that use heat from an oxyfuel gas flame. The necessary temperature is maintained by means of gas flames obtained from the combustion of a fuel gas and oxygen. When an oxyfuel gas cutting operation is described, the fuel gas must be specified. There are a number of fuel gases used. The most popular is acetylene. Natural gas is widely used, as is propane, methylacetylene–propadiene stabilized, and various trade name

fuel gases. Hydrogen is rarely used. Gasoline can even be used but is not popular. Each fuel gas has its particular characteristics and may require slightly different apparatus because of these characteristics. The characteristics relate to the flame temperatures, heat content, oxygen fuel gas ratios, and so on. The general concept of oxyfuel gas cutting is similar no matter what fuel gas is used. It is the oxygen jet that makes the cut in steel, and cutting speed depends on how efficiently the oxygen reacts with the steel. Oxygen for cutting must be 99% pure. If purity is less, cutting speed and efficiency will be reduced. For simplicity, we confine our discussion to the use of acetylene.

The generation of heat by combustion of acetylene and oxygen was described previously. This heat is used to bring the base metal steel up to its kindling temperature where it will ignite and burn in an atmosphere of pure oxygen. The chemical formula for three of the oxidation reactions is as follows:

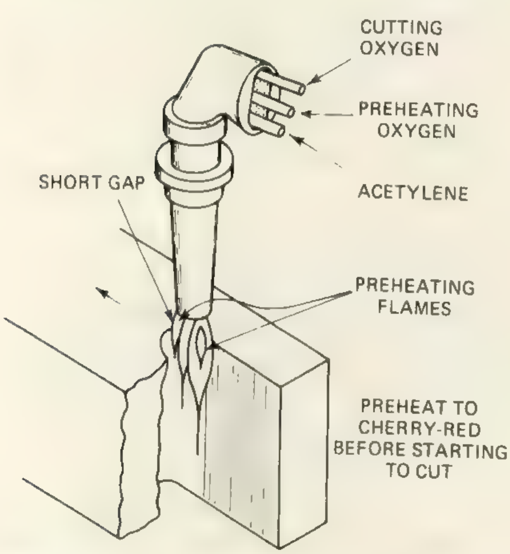
$$2Fe + O_2 = FeO + \text{heat (270 kJ)}$$
$$3Fe + 2O_2 = Fe_3O_4 + \text{heat (1100 kJ)}$$
$$2Fe + 1.5O_2 = Fe_2O_3 + \text{heat}$$

At elevated temperatures all of the iron oxides are produced in the cutting zone.

The oxyacetylene cutting torch is used to heat the steel by increasing the temperature to its kindling point and then by introducing a stream of pure oxygen to create the burning or rapid oxidation of the steel. The stream of oxygen also assists in removing the material from the cut (Figure 9-1).

Steel and a number of other metals are flame cut with the oxyfuel gas cutting process. The following conditions must apply:

FIGURE 9-1 Process diagram oxygen cutting.



1. The melting point of the material must be above its kindling temperature in oxygen.
2. The oxides of the metal should melt at a lower temperature than the metal itself and below the temperature that is developed by cutting.
3. The heat produced by the combustion of the metal with oxygen must be sufficient to maintain the oxygen cutting operation.
4. The thermal conductivity must be low enough so that the material can be brought to its kindling temperature.
5. The oxides formed in cutting should be fluid when molten so as not to interrupt the cutting operation.

Iron and low-carbon steel fit all the listed requirements and are readily oxygen flame cut. Cast iron is not readily flame cut, because the kindling temperature is above the melting point. It also has a refractory silicate oxide which produces a slag covering. Chrome–nickel stainless steels cannot be flame cut with the normal technique, because of the refractory chromium oxide formed on the surface. Nonferrous metals such as copper and aluminum have refractory oxide coverings which prohibit normal oxygen flame cutting; in addition, they have a high thermal conductivity.

When flame cutting,[1] the preheating flame should be neutral or oxidizing. A reducing or carbonizing flame should not be used. Figure 9-2 shows the flame cutting

FIGURE 9-2 Manual oxyacetylene cutting operation.

Material Thickness		Cutting Orifice Dia. (center hole)			Approx. Press. of Gas		Travel Speed Manual	Travel Speed Mechanized
in.	mm	Drill size	in.	mm	Acetylene psi	Oxygen psi	in./min.	in./min.
1/8	3.2	60	0.040	1.0	3	10	20-22	22
1/4	6.4	60	0.040	1.0	3	15	16-18	20
3/8	9.5	55	0.052	1.3	3	20	14-16	19
1/2	12.7	55	0.052	1.3	3	25	12-14	17
3/4	19.0	55	0.052	1.3	4	30	10-12	15
1	25.4	53	0.060	1.5	4	35	8-11	14
1-1/2	38.1	53	0.060	1.5	4	40	6-7-1/2	12
2	50.8	49	0.073	1.9	4	45	5-1/2-7	10
3	76.2	49	0.073	1.9	5	50	5-6-1/2	8
4	101.6	49	0.073	1.9	5	55	4-5	7
5	127.0	45	0.082	2.1	5	60	3-1/2-4-1/2	6
6	152.4	45	0.082	2.1	6	70	3-4	5
8	203.2	45	0.082	2.1	6	75	3	4

FIGURE 9-3 Schedule for oxyacetylene flame cutting of carbon steels.

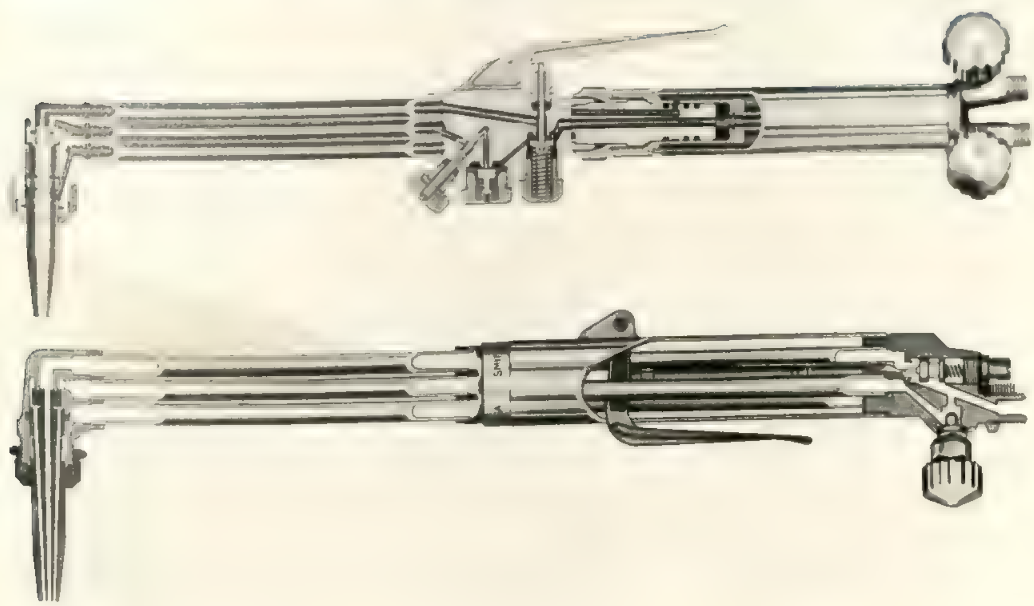
operation being manually performed. The schedule for flame cutting clean mild steel is shown in Figure 9-3.

Torches are available for either welding or cutting. By placing the cutting torch attachment on the torch body it is used for manual flame cutting. Figure 9-4 shows a manual oxyacetylene flame cutting torch. Various sizes of tips can be used for manual flame cutting. The numbering system for tips is not standardized and most manufacturers use their own tip number system. Each system is, however, based on the size of the oxygen cutting orifice of the tip. These are related to drill sizes. Different tip sizes are required for cutting different thicknesses of carbon steel. The manual cutting torch and oxygen and acetylene cylinders and regulators are shown in Figure 9-5. Semi-automatic cutting is shown in Figure 9-6.

For cutting with mechanized travel, the same types of tips can be used. High-speed tips, with a specially shaped oxygen orifice, provide for higher-speed cutting and are normally used. The schedule shown provides cutting speeds with normal tips; the speeds can be increased 25 to 50% when using high-speed tips. Mechanical cutting with a portable motorized carriage is shown in Figure 9-7.

Automatic shape-cutting machines are widely used by the metalworking industry. These machines can carry several torches and cut a number of pieces simultaneously. They may be of the gantry or cantilever type. They

FIGURE 9-4 Two styles of manual cutting torches.



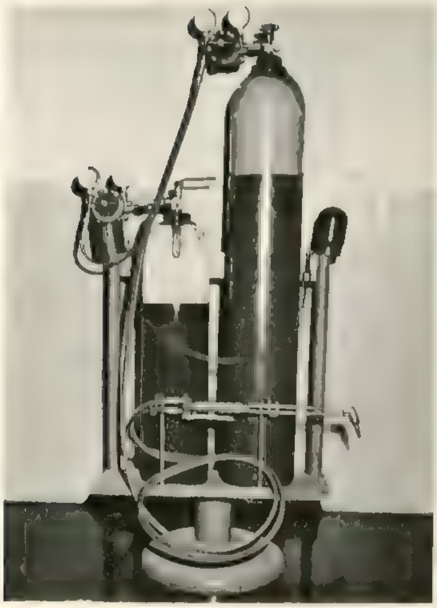
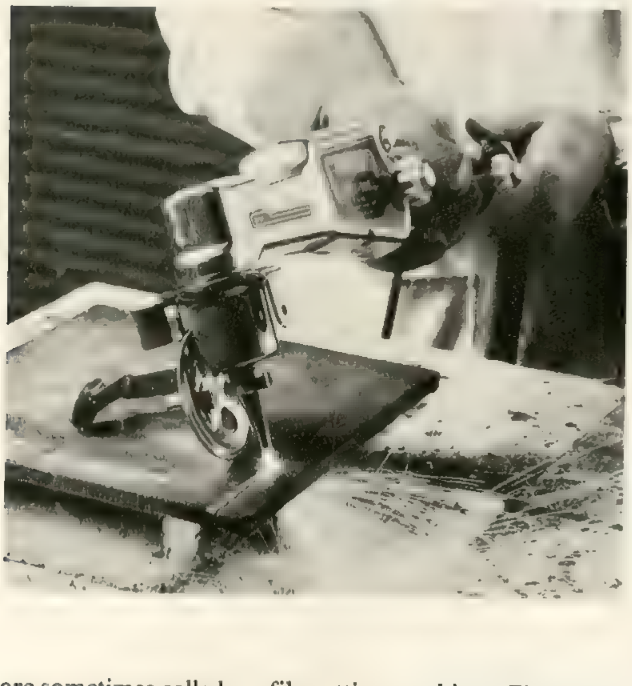


FIGURE 9-5 Complete manual oxygen cutting equipment.

FIGURE 9-6 Semiautomatic oxygen cutting equipment.



are sometimes called profile cutting machines. Figure 9-8 shows four pieces being cut. Shape cutting machines have evolved from simple devices that carried one torch that was guided by tracks or cams. Automatic machines are specified by the width of plate they can accommodate, the number of torches, and the type of tracing equipment employed. Fully automatic machines are guided by photocell-type tracing devices. The most modern multi-torch cutting machines are directed by numerically controlled equipment. No matter what type of tracing control system is used, the cutting operation is essentially the same. Figure 9-9 shows an automatic oxygen cutting machine utilizing the electric eye tracing device. This equipment pioneered chain cutting, which led to the newest numerically controlled oxygen cutting equipment shown in Figure 9-10. Chain cutting is accomplished by leaving small links of metal between adjacent pieces. This eliminates the need to start and stop the torch until the total cut is completed. The link is cut by a hand torch as the parts are removed from the cutting table. Another improvement of productivity is the nesting of parts to be cut from a piece of steel. This is done by specialized software programs in a computer. By the use of such a program, the amount of scrap is drastically reduced.

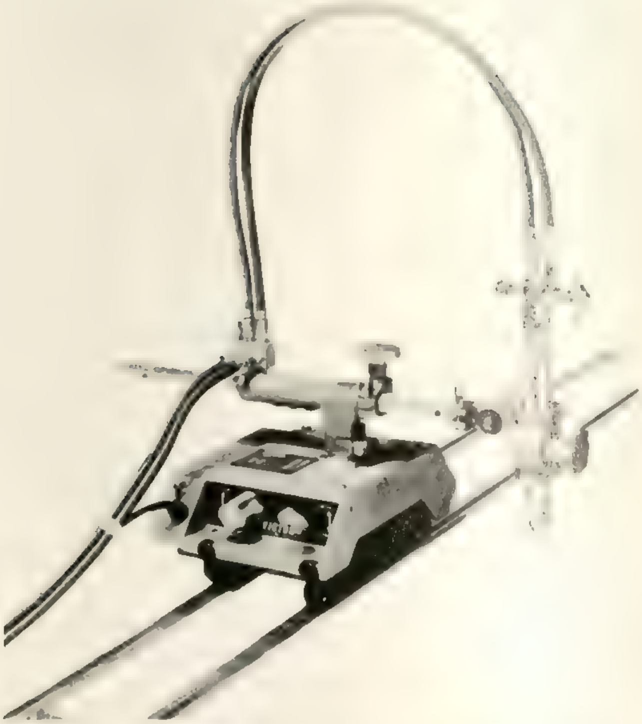


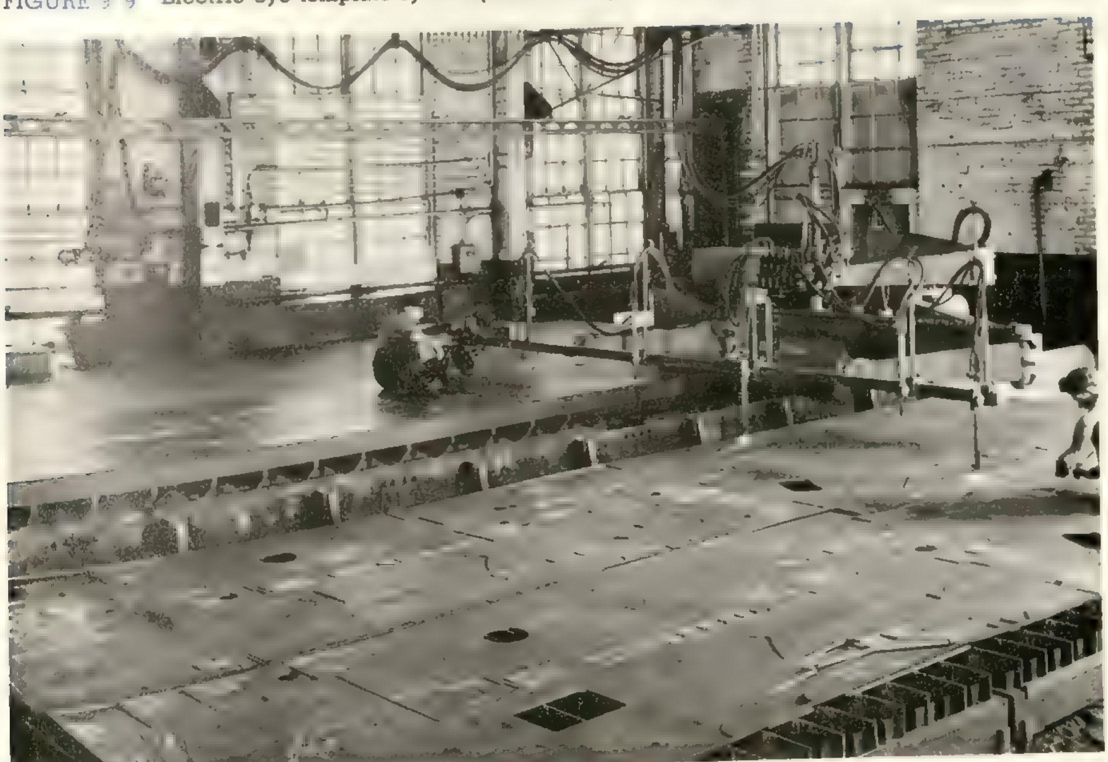
FIGURE 9-7 Mechanized cutting with portable machine.

One of the newer advances in automatic flame cutting is the generation of bevel cuts on contour-shaped parts. This breakthrough has made the use of numerically controlled oxygen cutting equipment even more productive. A bevel cut on medium-thickness material is shown in Figure 9-11.

Many specialized automatic oxygen cutting machines are available for specific purposes. Special machines are available for cutting sprockets and other precise items. Oxygen cutting machines are available for cutting pipe to fit other pipe at different angles and of different diameters. These are quite complex and have

FIGURE 9-8 Automatic shape-cutting machine (four torches).

FIGURE 9-9 Electric eye template system (two torches).



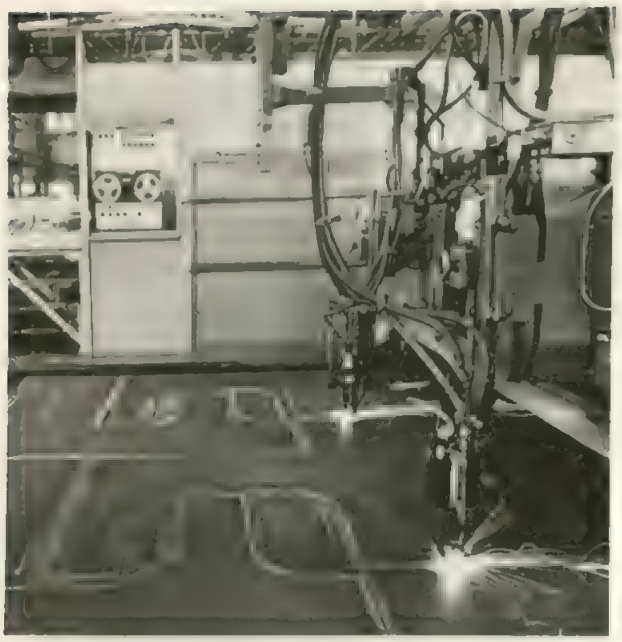
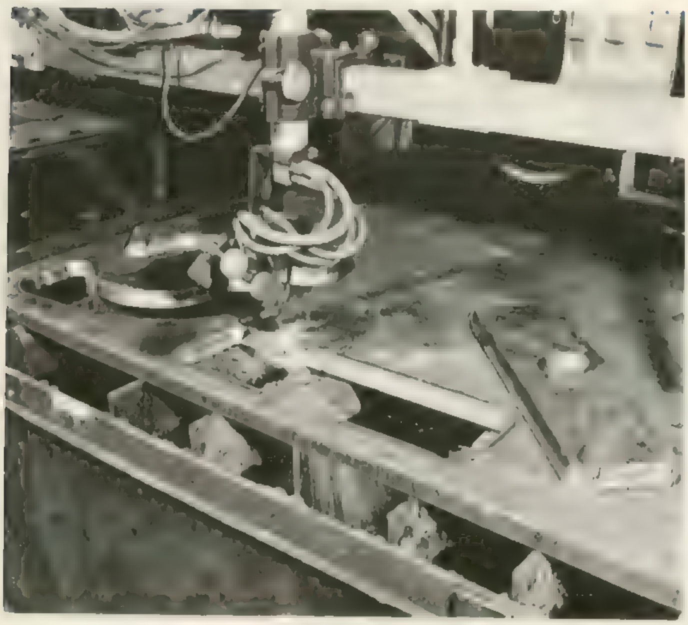


FIGURE 9-10 Numerical controlled oxygen cutting system.

FIGURE 9-11 Automatic bevel-cut procedure.



built-in contour templates to accommodate different cuts and bevels on the pipe. Other types of machines are designed for cutting holes in drum heads, test specimens, and so on. Two or three torches can be used to prepare groove bevels for straight-line cuts (Figure 9-12). Extremely smooth oxygen-cut surfaces can be produced when schedules are followed and all equipment is in proper operating condition. Figure 9-13 shows the oxygen-cut

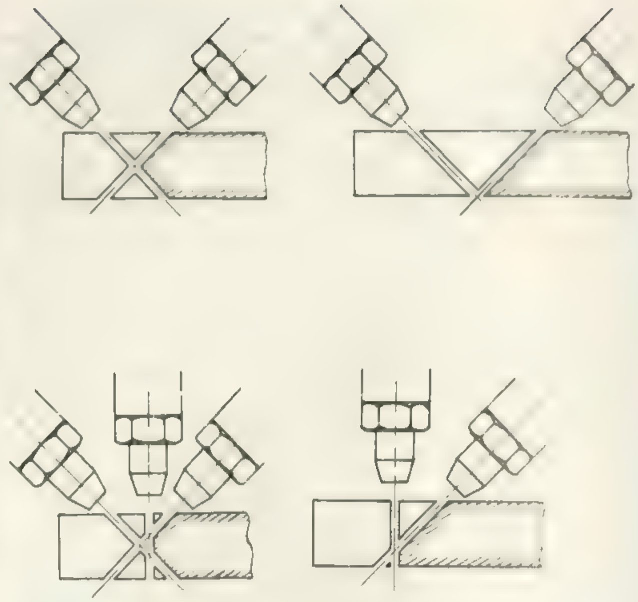


FIGURE 9-12 Method of cutting bevels.

surfaces made manually and gives the probable cause of subquality cuts.

The American Welding Society has provided a criteria for describing oxygen-cut surfaces. This publication includes a plastic replica showing surface reference guide or oxygen cutting at four different levels.[2] It includes terms for describing oxygen-cut surfaces, including flatness, angularity, roughness, top edge rounding, notch, and slags. Figure 9-14 shows the correct and incorrect adjustments for the machine and the torch.[3]

Dimensional tolerances for flame cutting depend largely on the thickness of the material and the size of the part. In medium thicknesses the dimensions of small parts can be held within $\pm\frac{1}{16}$ in. (1.6 mm). Sprocket wheels for driving caterpillar-type treads are oxygen flame cut and used without further finishing. On larger parts the tolerance is not as close, and when chain burning is employed, warpage can create distortion and dimensional problems.

The introduction of the water table has improved large automatic shape cutting operations. Use of the water table has several advantages. It greatly reduces the particulate matter released into the atmosphere by the oxygen cutting operation. It reduces distortion because the water in contact with the underside of the metal being cut eliminates the heat buildup in the metal. The water level can be raised or lowered, and it is raised during the cutting operation so that it is in contact with the metal being cut. Water tables include mechanisms for collecting the slag for easy disposal.

Stack cutting is the oxygen cutting of stacked metal sheets or plates arranged so that all the plates are severed by a single cut. In this way the total thickness of

FIGURE 9-13 Surface of flame-cut edges.

the stack is considered the same as the equivalent thickness of a solid piece of metal. When stack cutting, particularly thicker material, the cut is often lost because the adjacent plates may not be in intimate contact with each other. The preheat may not be sufficient on the lower plate to bring it to the kindling temperature and therefore the oxygen stream will no longer cut through the remaining portion of the stack. One way to overcome this problem is to use the metal powder cutting process. By means of the metal powder and its reaction in the oxygen the cut is completed across separations between adjacent plates.

Many special cutting tips for specific applications are available. These are used for flame gouging, to remove weld defects, and for edge preparation. Other tips are designed for rivet head removal, and others for removing risers from castings, and for shaping surfaces. A variety of tips are available and they can be used with either manual or mechanized equipment.

Metal Powder Cutting

Metal powder cutting (POC) is an oxygen cutting process that uses heat from an oxyfuel gas flame, with iron or other metal powder to aid cutting. This process is used for cutting cast iron, chrome-nickel stainless steels, and some high-alloy steels. The process uses finely divided material, usually iron powder, added to the cutting-oxygen stream. The powder is heated as it passes through the oxyacetylene preheat flames and almost immediately oxidizes or ignites in the stream of the cutting oxygen. A special apparatus to carry the powder to the cutting tip must be added to the torch. A powder dispenser is also required. Compressed air is used to carry the powder to the torch.

The oxidation or burning of the iron powder provides a much higher temperature in the oxygen stream. This plus the chemical reaction in the flame allows the cutting-oxygen stream to oxidize the metal being cut con-

Correct Adjustments
Top edge sharp.
Cut surface smooth, draglines barely visible.
Face of cut square.
Oxide, if any, easily removed.
Bottom edge sharp.

Cutting Speed too Slow
Top edge melted and rounded.
Free of cut irregular, with deep gouges.
Bottom edge very rough and irregular.
Possibly oxide tightly adhering to the bottom surface of the plate.

Cutting Speed too Fast
Top edge fairly sharp but with slight beading.
Draglines have pronounced backward rake.
Considerable undercutting just below top edge.
Bottom edge rounded.
Final corner uncut.

Preheat Flames too High Above the Work
Top edge badly melted and rounded over.
Slight undercutting just below top edge.
Face of cut otherwise square.
Bottom edge sharp.

Preheat Flames too Close to the Work
Top edge slightly rounded.
Heavy beads along top edge.
Face of cut smooth and square.
Bottom edge sharp.
Could be considered a fairly good cut.

Cutting-Oxygen Pressure too High
Even bead entire length of top edge.
Considerable undercutting below top edge.
Noticeable taper from top to bottom of cut.
Face of cut smooth.
Bottom edge sharp.

Preheat Flames too Long
Top edge rounded over.
Heavy bead entire length of top edge.
Considerable taper from top to bottom of cut.
Face of cut smooth, with draglines barely visible.
Bottom edge sharp.

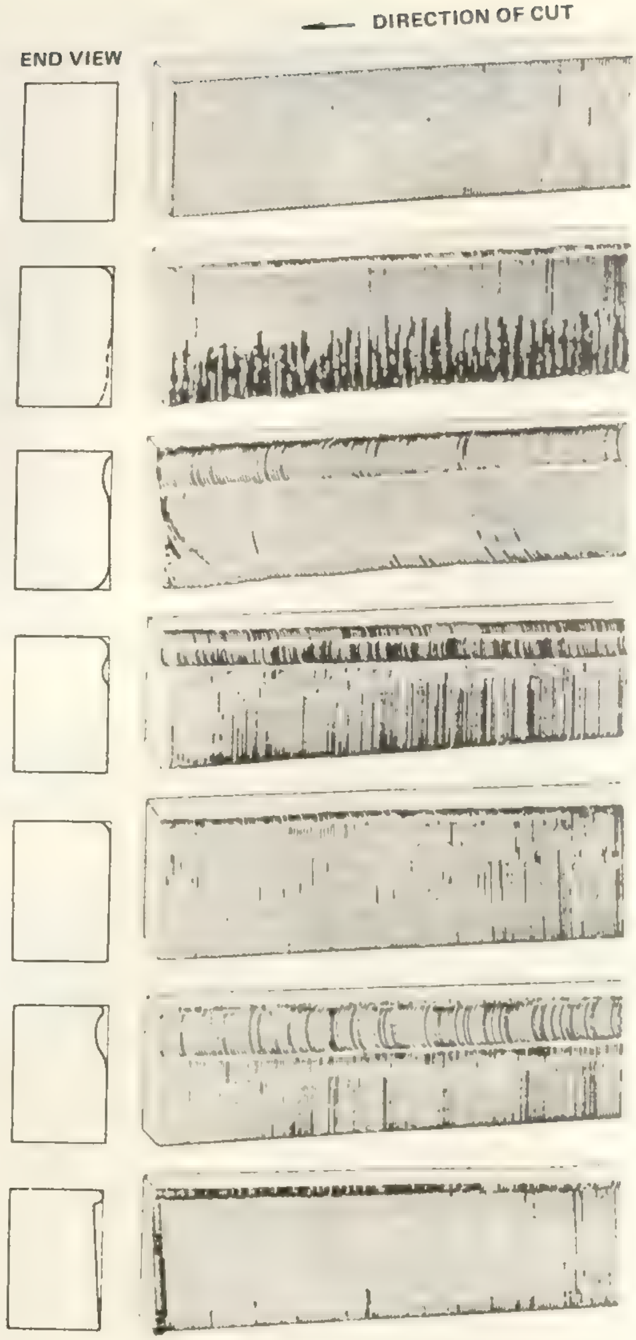


FIGURE 9-14 Machine cut surfaces: guide for oxygen cutting. (*Source*: Air Products and Chemicals, Inc.)

tinuously in the same manner as when cutting carbon steels. By the use of iron powder in the oxygen stream it is possible to start cuts without preheating the base material. Powder cutting has found its broadest use in the cutting of cast iron and stainless steel. It is used for removing gates and risers from iron and stainless steel castings. The same basic process can also be used for scarfing to condition billets, blooms, and slabs, in steel mills. It creates large amounts of smoke.

Cutting speeds and cutting oxygen pressures are similar to those used when cutting carbon steels. For heavier material over 1 in. thick (25 mm) a nozzle one size larger should be used. Powder flow requirements vary from ¼ to ½ lb (0.11 to 0.23 kg) of iron powder per minute of cutting. Powder tends to leave a scale on the cut surface which can easily be removed as the surface cools. This is a rather special application process and is used only where required. It is not popular.

Chemical Flux Cutting

Chemical flux cutting (FOC) is an oxygen cutting process that severs metals using a chemical flux to facilitate cutting. Powdered chemicals are sometimes used the same way as iron powder is used in the metal powder cutting process. This process is sometimes called flux injection cutting. Flux is introduced into the cut to combine with the refractory oxides and make them a soluble compound. The chemical fluxes may be salts of sodium such as sodium carbonate. Chemical flux cutting process is of minor industrial significance.

Oxygen Lance Cutting

Oxygen lance cutting (LOC) is an oxygen cutting process used to sever metals with oxygen supplied through a consumable tube or lance. The preheat to start the cutting is obtained by other means. This is sometimes called oxygen lancing. The oxygen lance is a length of pipe or tubing used to carry oxygen to the point of cutting. It uses a small (⅛ or ¼ in. nominal) black iron pipe connected to a suitable handle, which contains a shutoff valve. This handle is connected to the oxygen supply hose. The main difference between the oxygen lance and an ordinary flame cutting torch is that there is no preheat flame to maintain the material at the kindling temperature. The lance is consumed as it makes a cut. The principle use of the oxygen lance is the cutting of hot metal in steel mills. The steel is sufficiently heated so that the oxygen will cause rapid oxidation and cutting to occur. For other heavy or deep cuts a standard torch is used to bring the surface of the metal to kindling temperature. The end of the oxygen lance becomes hot and supplies iron to the reaction to maintain the high temperature.

There is a variation to the oxygen lance cutting process that uses a composite consumable tube. In one case the steel tube is filled with either aluminum or magnesium wires. In another it is a concentric tube of nonferrous metal. The aluminum or magnesium readily oxidize in the oxygen-rich atmosphere and increase the temperature of the reaction. A very high temperature is generated, on the order of 10,000 °F. The operation reaction can be started by means of a flame from the torch to heat the end of the rod or by means of an arc struck between the rod and the workpiece. It will continue as long as oxygen is fed through the tube. The tremendous amount of heat produced is sufficient to melt concrete, bricks, and other nonmetals. The composite rod or tube can be used to cut concrete or masonry walls. It will also cut slag, rocks, and all metals. It can also be used under water. Rods of this type are known by various trade names, such as Oxy-Lance, Hot-Rod, and Burning-Bar. These rods are known as exothermic since there is a reaction between the aluminum or magnesium and oxygen to produce high heat. Extra special safety precautions should be taken due to high heat and smoke produced by these rods.

Oxygen Arc Cutting

Oxygen arc cutting (AOC) is an oxygen cutting process that uses an arc between the workpiece and a consumable tubular electrode through which oxygen is directed to the workpiece. This process requires a specialized combination electrode holder and oxygen torch. A conventional constant-current welding machine and special tubular covered electrodes are used. This process will cut high-chrome–nickel stainless steels, high-alloy steels, and nonferrous metals. The high-temperature heat source is an arc between the special covered tubular electrode and the metal to be cut. As soon as the arc is established a valve on the electrode holder is depressed and oxygen is introduced through the tubular electrode to the arc. The oxygen causes the material to burn and the stream helps remove the material from the cut. Steel from the electrode plus the flux from the covering assist in making the cut. They combine with the oxides and create so much heat that thermal conductivity cannot remove the heat quickly enough to extinguish the oxidation reaction. This process will routinely cut aluminum, copper, brasses, bronzes, Monel, Inconel, nickel, cast iron, stainless steel, and high-alloy steels. The quality of the cut is not as good as the quality of an oxygen cut on mild steel, but sufficient for many applications. Material from ¼ to 3 in. (6.4 to 75 mm) can be cut with the process. The electric current ranges from 150 to 250 A and oxygen pressure of 3 to 60 psi (0.21 to 4.2 kg/cm^2) may be used. Electrodes are normally $\frac{3}{16}$ in. (4.8 mm) in diameter and 18 in. (450 mm) long. They are suitable for ac or dc use. This process is used for salvage work, as well as for manufacturing and maintenance operations.

9-2 ARC CUTTING

There are a number of thermal cutting processes that are defined by the American Welding Society. These processes utilize heat and thus differ from mechanical cutting processes such as sawing, shearing, blanking, water jet cutting, and so on.

The arc cutting processes are "a group of thermal cutting processes that sever or remove metal by melting with the heat of an arc between an electrode and the workpiece." Within this group is air carbon arc cutting, carbon arc cutting, gas tungsten arc cutting, shielded metal arc cutting, gas metal arc cutting, and plasma arc cutting. The thermal cutting processes can be applied by means of manual, semiautomatic, machine, or automatic methods.

Air Carbon Arc Cutting

Air carbon arc cutting (CAC-A) is "a carbon arc cutting process variation that removes molten metal with a jet of air." It is also used for gouging.

A high-velocity air jet traveling parallel to the carbon electrode strikes the molten metal puddle just behind the arc and blows the molten metal out of the immediate area. Figure 9-15 shows the operation of the process. It shows the arc between the carbon electrode and the work and the air stream parallel to the electrode coming from the special electrode holder.

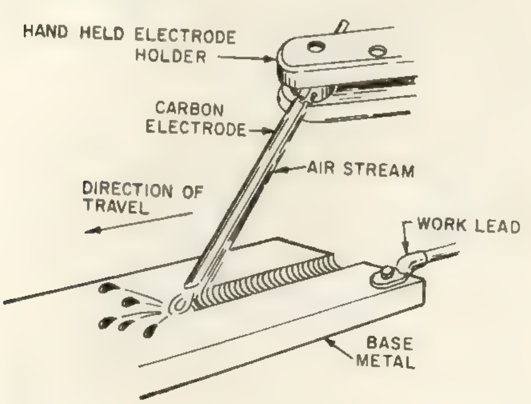
The air carbon arc cutting process is used to cut metal and to gouge out defective metal, to remove inferior welds, for root gouging of full-penetration welds, and to prepare grooves for welding. Air carbon arc cutting is used when slightly ragged edges are not objectionable. The area of the cut is small, and, since the metal is melted and removed quickly, the surrounding area does not reach high temperatures. This reduces the tendency towards distortion and cracking.

The air carbon arc cutting and gouging process is normally manually operated. The apparatus can be mounted on a travel carriage and thus considered machine cutting or gouging. Special applications have been made where cylindrical work has been placed on a lathe-like device and rotated under the air carbon arc torch.

The air carbon arc cutting process can be used in all positions. It can also be used for gouging in all positions. Use in the overhead position requires a high degree of skill. The air carbon arc process can be used for cutting or gouging most of the common metals. This, as well as current and polarity, is given in Figure 9-16.

The process is not recommended for weld preparation for stainless steel, titanium, zirconium, and other similar metals without subsequent cleaning. Cleaning, usually by grinding, must remove all of the surface carbonized material adjacent to the cut. The process can be used to cut these materials for scrap for remelting.

FIGURE 9-15 Process diagram for air carbon arc cutting or gouging.



Metal	Current Type	Electrode Polarity
Aluminums	DC	Positive
Copper and alloys	AC	—
Iron, cast, malleable, etc.	DC	Negative
Magnesium	DC	Positive
Nickel and alloys	AC	—
Carbon steels	DC	Positive
Stainless steels	DC	Positive

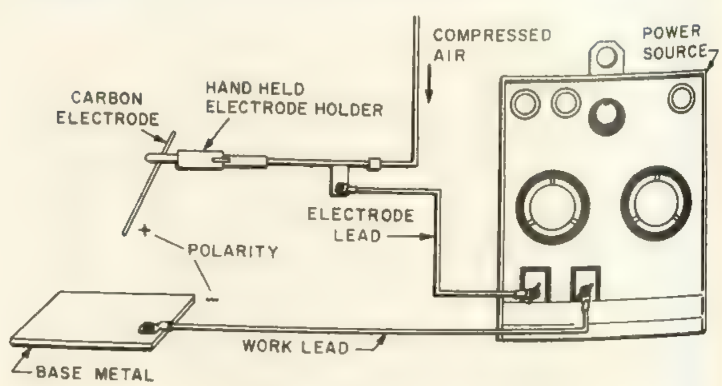
FIGURE 9-16 Metals that can be cut with AAC

The circuit diagram for air carbon arc cutting or gouging is shown in Figure 9-17. Normally, conventional welding machines with constant current are used. Constant voltage can be used with this process. When using a CV power source, precautions must be taken to operate it within its rated output. Alternating-current power sources having conventional drooping characteristics can also be used for special applications. Ac carbon electrodes must be used.

Equipment required is shown by the block diagram. Special heavy-duty high-current machines have been made specifically for the air carbon arc process. This is because of extremely high currents used for the large carbon electrodes.

The electrode holder shown in Figure 9-18 is designed for the air carbon arc process. The electrode holder and a copper-coated electrode are also shown. The holder includes a small circular grip head which contains the air jets for directing the compressed air along the electrode. It also has a groove for gripping the electrode. This head can be rotated to allow different angles of electrode with respect to the holder. A heavy electrical lead and an air supply hose are connected to the holder through a terminal block. A valve is included in the holder for turning the compressed air on and off. Holders are available in several sizes, depending on the duty cycle of the work performed, the welding current, and size of carbon electrode used. For extra-heavy-duty work, water-cooled holders are used.

FIGURE 9-17 Circuit block diagram AAC.



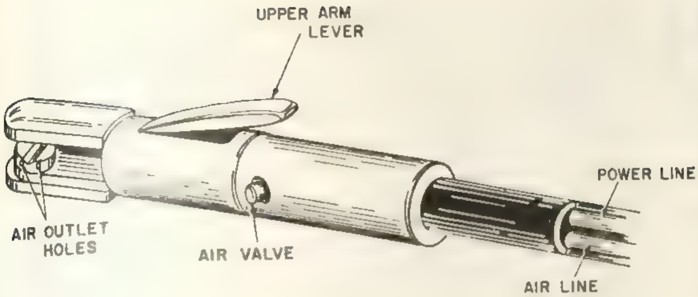


FIGURE 9-18 Electrode holder for CAC-A.

The air pressure is not critical but should range from 80 to 100 psi (550 to 690 kPa). The volume of compressed air required ranges from as low as 5 ft^3/min (2.5 liters/min) up to 50 ft^3/min (24 liters/min) for the largest carbon electrodes. A 1-horsepower compressor will supply sufficient air for smaller electrodes. It will require up to a 10-horsepower compressor when using the largest electrodes.

The carbon graphite electrodes are made of a mixture of carbon and a graphite plus a binder which is baked to produce a homogeneous structure. Electrodes come in several types. The plain uncoated electrode is less expensive, carries less current, and starts easier. The copper-coated electrode provides better electrical conductivity between it and the holder. The copper-coated electrode is better for maintaining the original diameter during operation; it lasts longer and carries higher current. Copper-coated electrodes are of two types, the dc type and the ac type. The composition ratio of the carbon and graphite is slightly different for these two types. The dc type is more common. The ac type contains special elements to stabilize the arc. The ac electrode is used for direct-current electrode negative when cutting cast irons. For normal use, the electrode is operated with the electrode positive. Electrodes range in diameter from 5/32 in. (4.0 mm) to 1 in. (25.4 mm). Electrodes are normally 12 in. (300 mm) long; however, 6-in. (150-mm) electrodes are available. Copper-coated electrodes with tapered socket joints are available for automatic operation and allow continuous operation. Figure 9-19 shows the electrode types and the arc current range for different sizes.

The procedure schedule for making grooves in steel is shown in Figure 9-20.[4]

To make a cut or a gouging operation the cutter strikes an arc and almost immediately starts the airflow. The electrode is pointed in the direction of travel with a push angle approximately 45° with the axis of the groove. The speed of travel, the electrode angle, and the electrode size and current determine the groove depth. Electrode diameter determines the groove width.

Electrode Type	Electrode Size in.	Electrode Size mm	Current Min.	Current Max.
DC (Plain) or AC (Copper Covered)	5/32	4.0	90	150
	3/16	4.8	150	200
	1/4	6.4	200	400
	5/16	7.9	250	450
	3/8	9.5	350	600
	1/2	12.7	600	1000
	5/8	15.9	800	1200
	3/4	19.1	1200	1600
	1	25.4	1800	2200

Polarity of electrode is positive (reverse polarity).

Note: For DC copper covered electrodes current can be increased 10%.

FIGURE 9-19 Size and current ranges for electrode types.

The normal safety precautions similar to carbon arc welding and shielded metal arc welding apply to air carbon cutting and gouging. However, two other precautions must be observed. First, the air blast will cause the molten metal to travel a very long distance. Metal deflection plates should be placed in front of the gouging operation. All combustible materials should be moved away from the work area. At high-current levels the mass of molten metal removed is quite large and will become a fire hazard if not properly contained.

The second factor is the high noise level. At high currents with high air pressure a very loud noise occurs. Ear protection, earmuffs or earplugs should be worn by the arc cutter.

The process is widely used for back gouging, for preparing joints, and for removing defective weld metal. It is also used in foundries for washing pads, removing risers, and removing defective areas of castings. Another major use is scrap preparation of metals to reduce them

Groove Width in.	mm	Groove Depth in.	mm	Electrode Dia. in.	mm	Amperes Direct Current	Volts Electrode Positive	Electrode Feed ipm	mm/min.	Travel Speed ipm	mm/min.
1/4	6.4	1/16	1.6	3/16	4.8	200	43	6.2	155.0	82.0	2050.0
9/32	7.1	1/8	3.2	3/16	4.8	200	40	6.7	167.5	38.2	955.0
5/16	7.9	3/16	4.8	3/16	4.8	190	42	6.7	167.5	27.2	680.0
5/16	7.9	1/4	6.4	3/16	4.8	(To make 1/4" deep groove, make two 1/8" deep passes.)					
5/16	7.9	3/32	2.4	1/4	6.4	270	40	4.0	100.0	54.0	1350.0
5/16	7.9	1/8	3.2	1/4	6.4	300	42	4.0	100.0	51.0	1275.0
5/16	7.9	3/16	4.8	1/4	6.4	300	40	6.7	167.5	38.2	955.0
5/16	7.9	1/4	6.4	1/4	6.4	320	42	6.2	155.0	29.5	737.5
5/16	7.9	3/8	9.5	1/4	6.4	320	46	3.6	90.0	15.0	375.0
3/8	9.5	1/8	3.2	5/16	7.9	320	40	3.0	75.0	65.5	1637.5
3/8	9.5	3/16	4.8	5/16	7.9	400	46	4.3	107.5	46.0	1150.0
3/8	9.5	1/4	6.4	5/16	7.9	420	42	3.8	95.0	31.2	780.0
3/8	9.5	1/2	12.7	5/16	7.9	540	42	5.6	140.0	27.2	680.0
7/16	11.1	1/8	3.2	3/8	9.5	560	42	4.2	105.0	82.0	2050.0
7/16	11.1	1/8	3.2	3/8	9.5	560	42	3.3	82.5	65.0	1625.0
7/16	11.1	3/16	4.8	3/8	9.5	560	42	2.6	65.0	41.0	1025.0
7/16	11.1	1/4	6.4	3/8	9.5	560	42	3.0	75.0	29.5	737.5
7/16	11.1	1/2	12.7	3/8	9.5	560	42	3.2	80.0	15.0	375.0
7/16	11.1	11/16	17.5	3/8	9.5	560	42	3.5	87.5	12.2	305.0
9/16	14.3	1/8	3.2	1/2	12.7	1200	45	3.0	75.0	34.0	850.0
9/16	14.3	1/4	6.4	1/2	12.7	1200	45	3.0	75.0	22.0	550.0
9/16	14.3	3/8	9.5	1/2	12.7	1200	45	3.0	75.0	20.7	517.5
9/16	14.3	1/2	12.7	1/2	12.7	1200	45	3.0	75.0	18.5	462.5
9/16	14.3	5/8	15.9	1/2	12.7	1200	45	3.0	75.0	15.0	375.0
9/16	14.3	3/4	19.1	1/2	12.7	1200	45	3.0	75.0	12.5	312.5
13/16	20.6	1/8	3.2	5/8	15.9	1300	42	2.5	62.5	44.5	1112.5
13/16	20.6	1/4	6.4	5/8	15.9	1300	42	2.5	62.5	29.5	737.5
13/16	20.6	3/8	9.5	5/8	15.9	1300	42	2.5	62.5	20.0	500.0
13/16	20.6	1/2	12.7	5/8	15.9	1300	42	2.5	62.5	14.5	362.5
13/16	20.6	5/8	15.9	5/8	15.9	1300	42	2.5	62.5	13.0	325.0
13/16	20.6	3/4	19.1	5/8	15.9	1300	42	2.5	62.5	11.0	275.0
13/16	20.6	1	25.4	5/8	15.9	1300	42	2.5	62.5	10.0	250.0

Notes: 1 For carbon steel
2 Combination of settings and multiple passes may be used for grooves deeper than 3/4".
3 All values are for DC copper-coated electrodes.
4 Air pressures 80-100 psi is recommended for 1/2" and 5/8" electrodes.
5 A head angle for 45 degrees is used for these settings.

FIGURE 9-20 Air carbon arc gouging procedure schedule. (From Ref. 4).

to proper size for handling. It is used also for scrapping of metal objects and for maintenance and salvage operations.

Carbon Arc Cutting

Carbon arc cutting (CAC) is "an arc cutting process that uses a carbon electrode." The process is similar to air carbon arc cutting except that the air blast is not employed. The process depends strictly on the heat input of the cabon arc to cause the metal to melt. The molten metal falls away by gravity to produce the cut. The process is relatively slow, a very ragged cut results, and it is used only when other cutting equipment is not available. It has little industrial significance.

Metal Arc Cutting

Metal arc cutting (MAC) is "any group of arc cutting processes which sever metals by melting them with the heat of an arc between a metal electrode and the base metal." When covered electrodes are used it is known as shielded metal arc cutting (SMAC).

The equipment required is identical to that required for shielded metal arc welding. When the heat input into the base metal exceeds the heat losses the molten metal pool becomes large and unmanageable. If the base metal is not too thick, the molten metal will fall away and create a hole or cut. The cut produced by the shielded metal arc cutting process is rough and is not normally used for preparing parts for welding. The metal arc cutting process

using covered electrodes is used only where a small cutting job is required and other means are not available for the purpose or in an emergency.

For metal arc cutting an electrode with deep penetrating qualities such as an E6010 or an E6011 should be used. A relatively small electrode should be used with a dc electrode negative. The current should be set much higher than normally used for welding. This will create a maximum amount of heat in the weld pool, which will soon fall away making the cut. This technique can also be used for cutting cast iron. On thick material a sawing action is required to make the cut and to allow the molten metal to fall away. If the electrode coating is made wet by dipping in water the electrode will melt somewhat more slowly so that more cut can be obtained per electrode.

The metal arc cutting technique can also be used for gouging when utilizing special electrodes. These special electrodes have an insulating type of coating which directs the arc. It is sometimes used for back gouging welds prior to making the backing weld. The schedule used for gouging is shown in Figure 9-21. The gouging-type electrode can be used for cutting. The gas metal arc (GMAC) can also be used for cutting.

Gas Tungsten Arc Cutting

Gas tungsten arc cutting (GTAC) is "an arc cutting process in which metals are severed by melting them with an arc between a single tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture."

The apparatus for gas tungsten arc cutting is identical to that used for gas tungsten arc welding. The gas tungsten arc is used to provide sufficient heat input so that the molten pool will become large and unmanageable and will fall away. Gas tungsten arc cutting is restricted to the thinner metals and can be used for cutting almost any metal in thin sections. The smoothness of the cut in thin materials is largely dependent on the skill of the arc cutter and the accuracy and uniformity of travel. Under ideal conditions smooth cuts can be made with gas tungsten arc welding on thin materials.

This process has largely been supplanted by plasma arc cutting and is of little industrial significance except for small jobs when other equipment is not available.

Plasma Arc Cutting

Plasma arc cutting (PAC) is an arc cutting process that uses a constricted arc and removes the molten metal with a high-velocity jet of ionized gas issuing from the constricting orifice.

There are two major variations: (1) the low-current plasma cutting system, which normally uses air for the plasma and is usually manually applied; and (2) the high-current plasma cutting system, which normally uses nitrogen for the plasma and is usually applied automatically. A variation of the high-current plasma system utilizes water to improve the quality of the cut. Low- and high-current plasma cutting is shown in Figure 9-22.

The operation of plasma cutting is very similar to the keyhole mode of plasma welding. For cutting, the keyhole is not allowed to close. Heat input of the plasma arc is very high and the heat losses cannot carry the heat away quickly enough. At a high velocity the plasma blows away the molten metal and produces the cut.

Plasma arc cutting has less of a detrimental metallurgical effect on the base metals than does oxygen cutting. Welding operations can often be performed directly over plasma-cut edges in aluminum and stainless

FIGURE 9-21 Shielded metal arc gouging procedure schedule.

Groove Width in.	Groove Width mm	Groove Depth in.	Groove Depth mm	Electrode Dia. in.	Electrode Dia. mm	Amperage Direct Current	Travel Speed ipm	Travel Speed mm/min.
3/16	4.8	1/32	0.8	1/8	3.2	210	71	1775
5/32	4.0	1/16	1.6	1/8	3.2	210	58	1450
1/4	6.4	3/32	2.4	1/8	3.2	210	47	1175
1/4	6.4	1/8	3.2	1/8	3.2	210	34	850
3/16	4.8	1/16	1.6	5/32	4.0	300	92	2300
1/4	6.4	3/32	2.4	5/32	4.0	300	71	1775
5/16	7.9	1/8	3.2	5/32	4.0	300	55	1375
5/16	7.9	5/32	4.0	5/32	4.0	300	43	1075
5/16	7.9	1/16	1.6	3/16	4.8	350	66	1650
3/8	9.5	1/8	3.2	3/16	4.8	350	50	1250
3/8	9.5	5/32	4.0	3/16	4.8	350	32	800
3/8	9.5	3/16	4.8	3/16	4.8	350	25	625

Note: (1) Flat and vertical down position
(2) Voltage will vary between 40 and 65 electrode negative (straight Polarity). Set welding machine to maximum open circuit voltage.

FIGURE 9–22 Plasma arc cutting: (a) manual, (b) mechanized.

steel. The very thin film on aluminum and on stainless steel edges is not detrimental and cannot be detected in the weld joint. In addition, they do not adversely affect the mechanical properties of the joint and cannot be seen in metallurgical examinations.

The plasma arc cutting process can be used in all positions. It can also be used for piercing holes and for gouging. The piercing capacity is usually half the cutting thickness capacity. In addition, plasma arc cutting can be used to cut metals underwater.

The plasma arc welding torch described previously is modified for cutting. It uses the pilot arc or non-transferred mode as well as the transferred mode during cutting. It can be used to cut all metals. Due to its high temperature, which approaches 30,000 °F (16,650 °C), high-melting-temperature oxides which coat many metals do not interfere with the operation. The torch will cut metals that cannot be cut with the oxygen cutting process since flame temperatures only approach 5600 °F (3100 °C). The metals cut with plasma arc cutting include aluminum, brass, bronze, copper, galvanized steel, coated or painted steel, mild steel, and stainless steel.

Plasma arc cutting can be used for chain cutting, contour cutting, and stack cutting. It is more efficient than oxyacetylene cutting for stack cutting.

The surface quality of the cut edge is equal to or better than that of oxyfuel gas cutting. The kerf is normally narrower than for oxyacetylene cutting and the angle of the cut is approximately 90°.

Low-Powered Plasma Arc Cutting In the low-powered plasma arc cutting variation, the maximum current is normally 125 A. The torch is relatively small, usually air cooled, and manually operated. Air is usually used for the plasma. Low-powered units can also be used with mechanized cutting systems and can utilize special devices to help as an aid for manual cutting (Figure 9-23). This shows a small circle-cutting attachment which improves the quality of the cut surface. Straight-line attachments are also used. In all cases the cutting speed is greater than the cutting speed of oxyacetylene cutting. The cutting speed versus material thickness for low-powered plasma arc cutting is shown in Figure 9-24.

Special plasma arc cutting equipment packages are available. These range in size from 30 to 50 to 120 A. Some of the power sources do not have current adjustments, but they all include power contactors since the maximum open-circuit voltage can be as high as 375 V. This keeps the open-circuit voltage from being present at the machine terminals or in the torch except when cutting. The package may also include the torch and cable, plasma gas regulator, and solenoid valve. The torches are air cooled and the machines may be adjusted for 20, 30, 40, 60A, or higher current output.

The low-powered plasma systems are used in place of oxyacetylene cutting torches for manual cutting in maintenance and repair. One of the popular applications has been auto body repair and other sheet metal work.

High-Powered Plasma Arc Cutting High-powered plasma arc cutting uses 100 to 500 A of current. In high-powered cutting, machine shape cutting apparatus is used. The equipment is similar to that used for oxygen flame

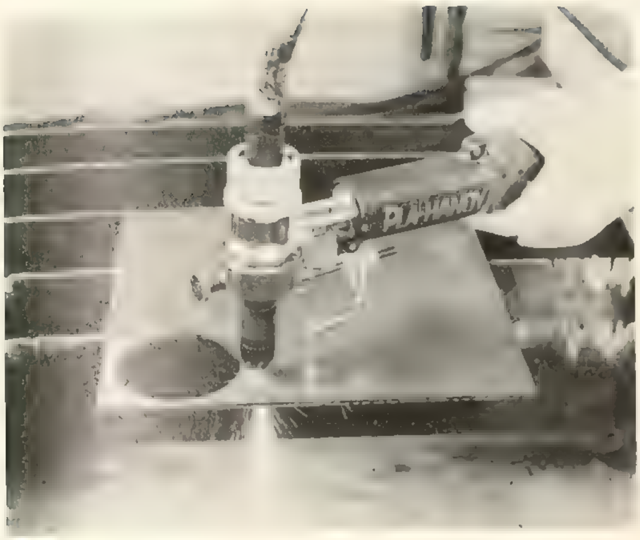


FIGURE 9-23 Plasma arc cutting with circle attachment.

cutting. A higher travel speed is required. Motion is controlled in the same manner as in oxygen cutting systems.

The heavy-duty plasma torches are water cooled. They will fit in the same torch holders as those used on automatic oxygen flame cutting machines. A water spray is sometimes used to surround the plasma to reduce smoke and noise. Worktables containing water, which is in contact with the underside of the metal being cut, also reduces noise and smoke. In some cases the water surface is above the top surface of the metal. The cutting speed versus material thickness for high-powered plasma arc cutting is shown in Figure 9-25. More information concerning this process variation is in the AWS "Recommended Practices for Plasma Arc Cutting."[5]

Control of the motion device, gas flow, and the power source is in a central control system which may be computer driven. Nitrogen is usually used for high-current plasma systems; however, in some cases, 80% argon plus 20% hydrogen is used. The plasma gas should be matched to the work being cut.

Water Injection Variation The water injection variation is an effort to reduce fumes and smoke produced by the high-powered plasma arc cutting process. Use of water in the plasma improves the quality of the cut on most materials.

Safety Considerations The noise level generated by the high-powered equipment is uncomfortable. The cutter should wear ear protection. For low-power cutting, special ear protection is not required.

For high-powered cutting, local exhaust is required since large amounts of fumes or particulate matter is generated. High-powered cutting should be done over a water reservoir so that the molten metal removed from the cut will fall in the water and help reduce the amount of fumes released into the air.

The normal protective clothing to protect the cutter from arc and molten metal should be worn. The helmet should be supplied with a No. 9 filter glass lens for heavy-duty cutting, although lighter shades can be

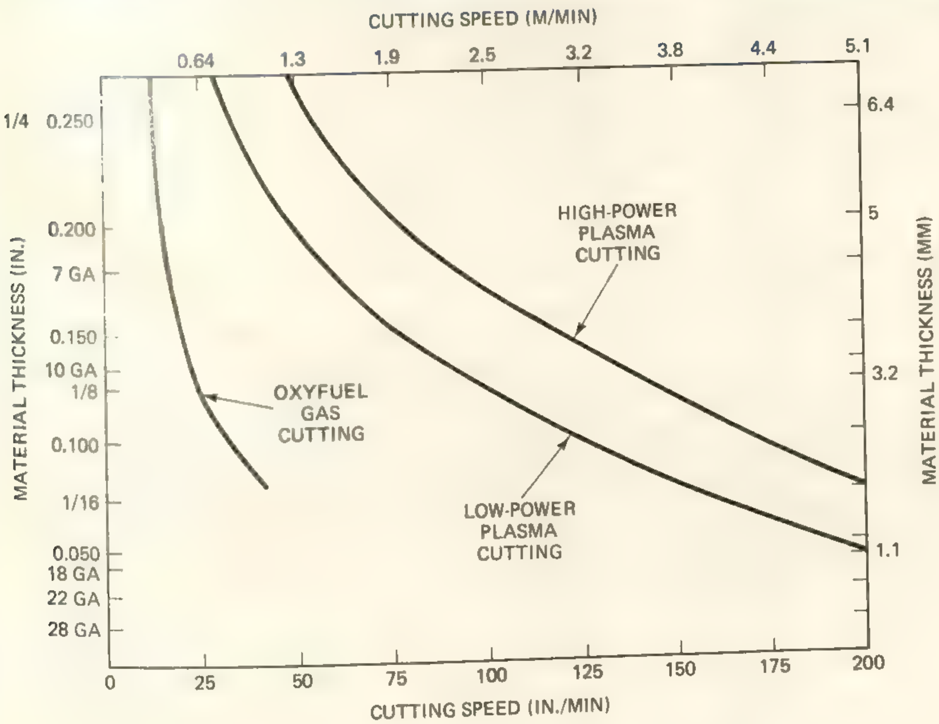


FIGURE 9-24 Plasma cutting steel sheet metal, air for plasma.

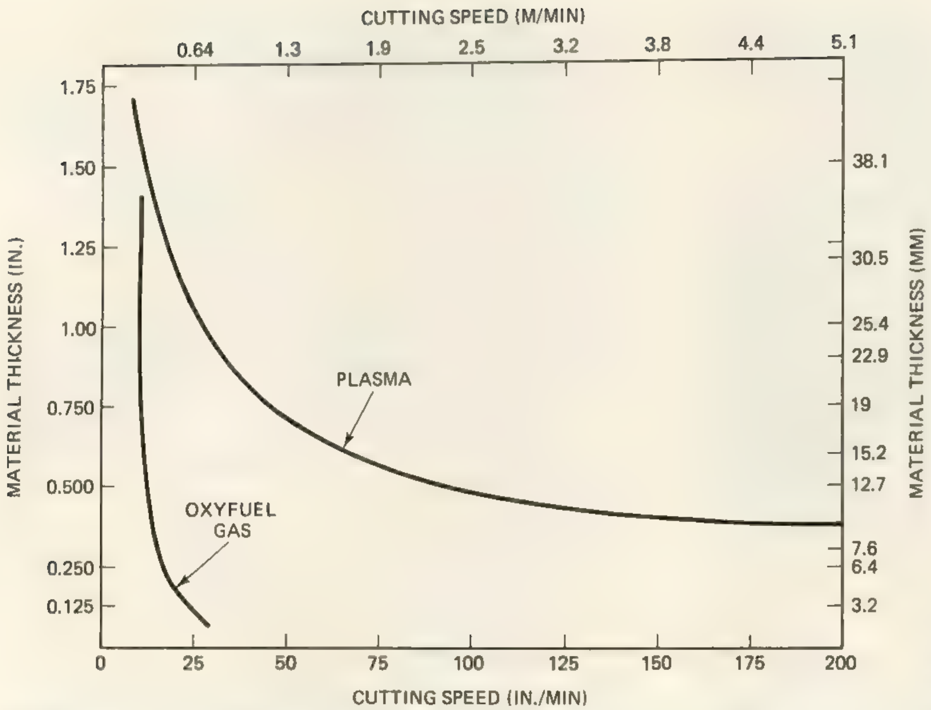


FIGURE 9-25 Plasma cutting steel plate material, air for plasma.

worn for low-powered cutting. Other safety considerations as outlined in Chapter 3 should be followed.

9-3 THERMAL SPRAYING

Thermal spraying (THSP) is a group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molton or semimolten condition on a substrate or base metal to form a thermal spray deposit. The surfacing material may be in the form of powder, rod, or wire.

There are three separate processes within this group: arc spraying, plasma arc spraying, and flame spraying. These three processes differ considerably since each uses a different source of heat and different apparatus. Thermal spraying was invented in 1913.

There are several variations of these processes. A variation of flame spray is the detonation method, which uses combustible gases but attains a much higher temperature and particle velocity. A variation of the plasma spray process is the plasma transferred arc method, which provides higher temperatures and is more of a welding process. A summary of thermal spraying surfacing methods is given in Figure 9-26.

The selection of the spraying process depends on the properties desired of the coating. Thermal spraying is utilized to provide surface coatings of different characteristics, such as coatings to reduce abrasive wear,

FIGURE 9-26 Thermal spray process for types of coating materials.

	THERMAL SPRAYING PROCESS				
	FLAME Oxyfuel Gas Combustion	DETONATION Oxyfuel Gas Pulsed Explosion	ARC Electric Arc, Two Wires	PLASMA Nontransferred Arc	PTA Plasma Transferred Arc
Heat source temperature	4700°F–5600°F	6000°F+	8000°F	15,000°F	15,000°F
Partical velocity	800 ft/sec	2500 ft/sec	800 ft/sec	1800 ft/sec	—
Coating Materials					
Wire–metal	Yes	No	Yes	Yes	Yes
Powder–metal	Yes	Yes	No	Yes	Yes
Powder–ceramic	Yes	Yes	No	No	No
Rod or cord ceramic and plastic	Yes	No	No	No	No

cavitation, or erosion. The coating may be either hard or soft. It may be used to provide thermal barriers for high-temperature protection. Thermal sprayed coatings improve atmosphere and water corrosion resistance. One of the major uses is to provide coating resistance to salt-water atmospheres. Another use is to restore dimensions to worn parts. The hardness and composition of the deposit are important and dictate whether the part will be machined or ground. Based on this decision, it is then necessary to determine the type of material that will be sprayed. If the spray material is available in wire form, the electric arc spray or the flame spray processes can be used. However, if it can be obtained only in a powder form, the flame spray or plasma spraying process must be used. The selection of materials for spraying is beyond the scope of this section. See the AWS "Thermal Spraying Practice, Theory and Application."[6]

Flame Spraying

Flame spraying (FLSP) is a thermal spraying process that uses an oxyfuel gas flame as a source of heat for melting the surfacing material. Compressed gas may or may not be used for atomizing and propelling the surfacing material to the workpiece or substrate. There are two major variations: One uses metal in wire form and the other uses materials in powder form. The method of flame spraying that uses powder is sometimes known as powder flame spraying. The method of flame spraying using wire is known as metallizing or wire flame spraying.

In both versions, the material is fed through a gun and nozzle and melted in the oxygen fuel gas flame. Atomizing, if required, is done by an air jet, which also propels the atomized particles to the workpiece. When wire is used for surfacing material, it is fed into the nozzle by an air-driven wire feeder and is melted in the gas flame. When powdered materials are used, they may be fed by gravity from a hopper, which is a part of the torch. In another system the powders are picked up by the oxygen fuel gas mixture, carried through the gun where they are melted, and propelled to the surface of the workpiece by the flame.

Figure 9-27 shows the flame spray process using wire. This version can spray metals that can be provided in wire form. The variation that uses powder can feed various materials. These include normal metal alloys, oxidation-resistant metals and alloys, and ceramics. Ceramics can be provided in rod or cord form. It provides sprayed surfaces that can have many different characteristics.

Detonation Gun Spraying

This is a variation of flame spraying and is an internal combustion method that produces a high-speed jet. It utilizes the energy of rapid explosions of oxygen and fuel gas mixtures rather than a steadily burning flame. The powder is introduced into the combustion chamber. When the gas mixture is ignited, a controlled detonation wave or flame front accelerates and heats the powder particles as it moves down the length of the combustion chamber. Exit particle velocities are extremely high and the temperature is higher than the normal flame temperature. After each injection of powder has been discharged, a pulse of inert gas purges the barrel and chamber. Multiple detonations during each second build up the coating. Temperatures above 5000 °F (2760 °C) and velocities of 2500 ft/sec are attained. The density of the deposited coating is extremely high and the bond with the workpiece is extremely good. Smooth deposits are achievable because of the high density of the deposit. This process is shown in Figure 9-28.

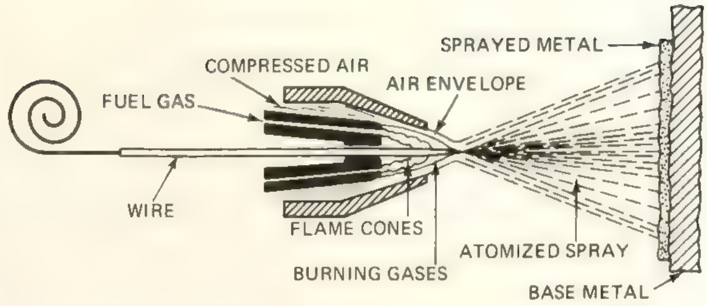


FIGURE 9-27 **Flame spray process.**

Arc Spraying

Arc spraying (ASP) is a thermal spraying process using an arc between two consumable electrodes of surfacing materials as a heat source, and a compressed gas to atomize and propel the surfacing material to the workpiece or substrate (Figure 9-29). The two consumable electrode wires are fed, by a wire feeder, to bring them together at an angle of approximately 30° and to maintain an arc between them. A compressed air jet is located behind and directly in line with the intersecting wires. The wires melt in the arc and the jet atomizes the melted metal and propels the fine molten particles to the workpiece. The power source for producing the arc is a direct-current constant-voltage welding machine. The wire feeder is similar to that used for gas metal arc welding except that it feeds two wires. The gun can be hand held or mounted in a holder with a movement mechanism. The part or the gun is moved with respect to the other to provide a coating surface on the part.

The welding current ranges from 300 to 500 A direct current, with the voltage ranging from 25 to 35 V. This system will deposit from 15 to 100 lb/hr of metal. The amount of metal deposited depends on the current level and the type of metal being sprayed. Wires for spraying are sized according to the Brown and Sharp wire gauge system. Normally either 14 gauge (0.064 in. or 1.6 mm)

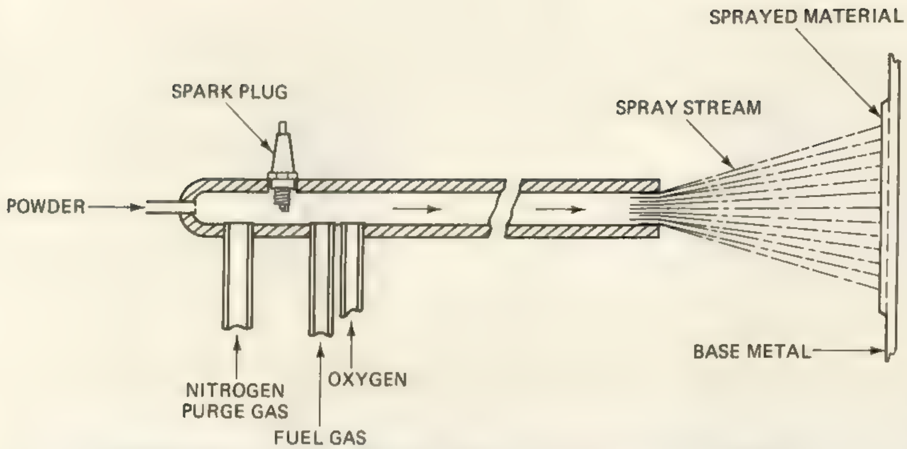


FIGURE 9-28 Detonation gun spray method.

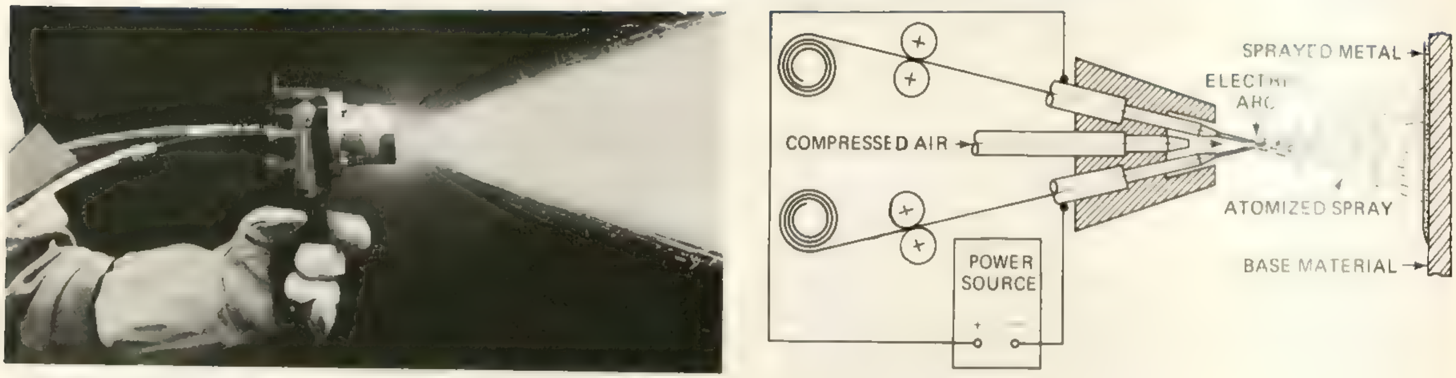


FIGURE 9-29 Arc spraying process.

or 11 gauge (0.091 in. or 2.3 mm) is used. Larger-diameter wires can be used.

The high temperature of the arc melts the electrode wire faster and deposits particles having a higher heat content and greater fluidity than in the flame spraying process. The deposition rates are from three to five times greater and the bond strength is greater. There is coalescence in addition to the mechanical bond. The deposit is more dense and coating strength is greater than when using flame spraying.

Dry compressed air is normally used for atomizing and propelling the molten metal. A pressure of 80 psi (5.7 kg/cm^2) and flow from 30 to 80 ft^3/min (14 to 38 liters/min) is used. Almost any metal that can be drawn into a small wire can be sprayed. Figure 9-30 is a list of metals that are arc sprayed.

Metal Sprayed	Spray Rate lb/hr/100A
Aluminum	5–7
Babbitt	—
Brass	10–12
Bronze	10–12
Copper	12–15
Molybdenum	—
Monel	11–13
Nickel	9–11
Stainless Steel	11–13
Carbon Steel	10–14
Tin	—
Zinc	20–25

FIGURE 9-30 Arc spraying—metals and spray rates.

Plasma Spraying

Plasma spraying (PSP) is a thermal spraying process in which a nontransferred arc of the gun is used to create an arc plasma for melting and propelling the surfacing material to the workpiece or substrate (Figure 9-31). Plasma spraying is sometimes called plasma flame spraying or plasma metallizing. It uses a nontransferred plasma arc, which is entirely within the plasma spray gun. The temperature is much higher than either arc spraying or flame spraying. Higher-temperature materials can be used for the coating. Most inorganic materials, which melt without decomposition, can be used. The material to be sprayed must be in a powder form since it is carried into the plasma spray gun suspended in a gas. The high-temperature plasma immediately melts the powdered

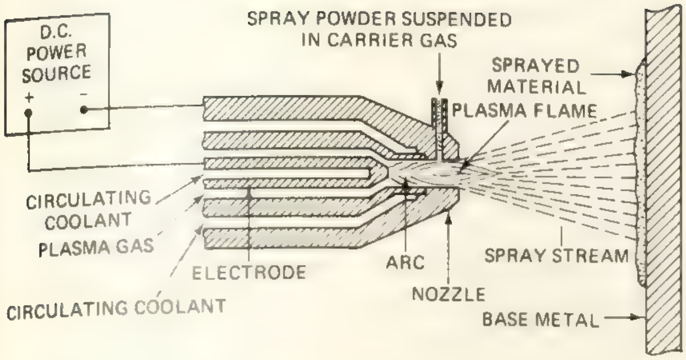


FIGURE 9-31 Plasma spray process.

material and propels it to the surface of the workpiece. Since inert gas and extra high temperatures are used, the mechanical and metallurgical properties of the coatings are generally superior to either flame spraying or arc spraying. This includes reduced porosity and improved bond tensile strengths. Coating density can reach 95%. The hardest metals known, and some with extremely high melting temperatures, can be sprayed with the plasma spraying process.

Plasma Transferred Arc Spraying

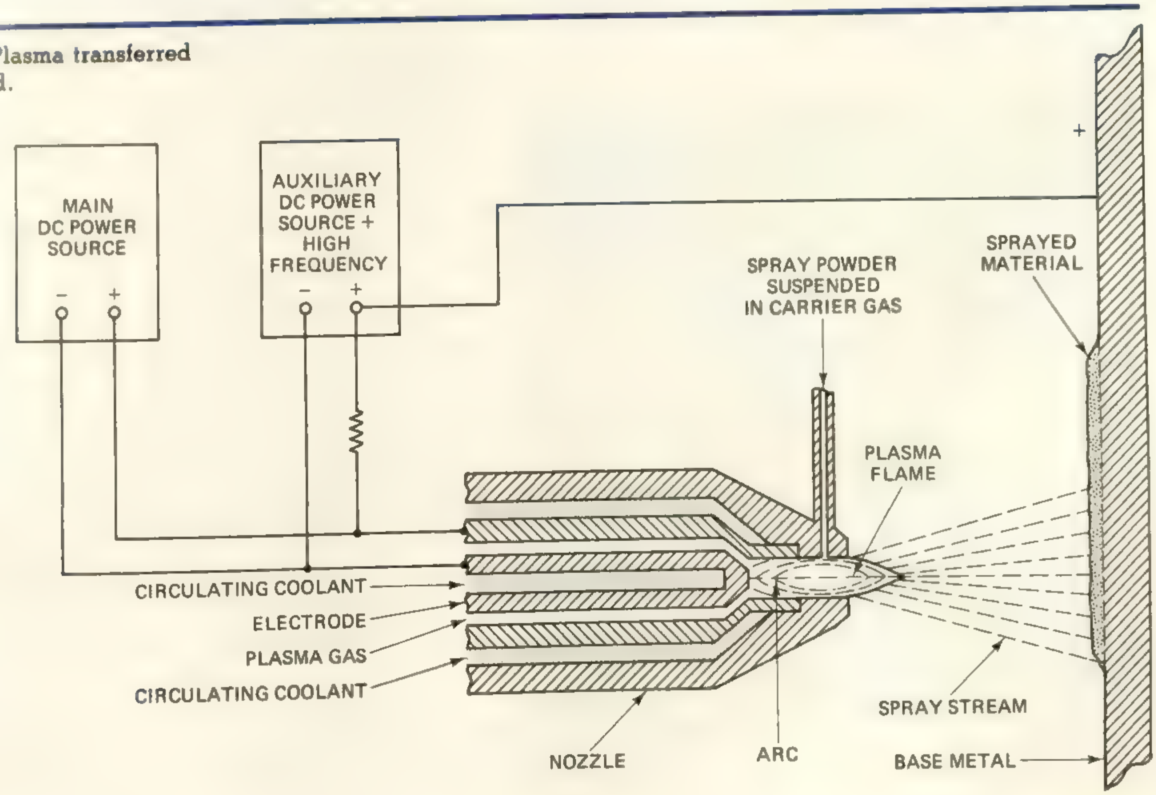
The plasma transferred arc (PTA) process is a combination of welding and thermal spraying processes. Powder or wire is introduced into the plasma arc stream issuing from the nozzle. The emitted spray forms a molten pool on the workpiece or substrate, which cools and solidifies as a deposit with parent metal dilution. The process uses equipment similar to plasma spray and plasma welding, and is shown in Figure 9-32.

In the PTA method, the electrical current from the nonconsumable tungsten electrode passes through the torch orifice and is carried by the plasma to the conductive workpiece. The powder or wire is introduced into the plasma as it exits the orifice. It is melted and transferred to the surface of the workpiece and is deposited. The heat of the metal being sprayed causes melting of the base metal or substrate, and there is dilution between the base metal and the sprayed material. The deposit is usually applied in greater thicknesses than a thermal sprayed coating. There is no slag to be removed and the completed deposit is smooth and uniform. A PTA deposit is generally more localized, denser, and is metallurgically bonded to the workpiece; however, the selection of coating materials and workpiece composition is more limited.

Preparation for Spraying

The most important aspect of thermal spraying is correct preparation of the workpiece. It must be clean. Machining is normally used to prepare round parts, such as shafting. When thermal spraying is used to correct a dimension, the part is usually machined undersize to allow a sufficient thickness of coating. For large flat areas, grit blasting is used. In any case, a roughened surface is preferred, but sharp corners should be avoided.

FIGURE 9-32 Plasma transferred arc spray method.



Spraying Operation

Spraying should be done immediately after the part is cleaned. If the part is not sprayed immediately, it should be protected from the atmosphere by wrapping with paper. If parts are extremely large, it may be necessary to preheat the part 200 to 400 °F (95 to 205 °C). Care must be exercised so that heat does not build up in the workpiece. This increases the possibility of cracking the sprayed surface. The part to be coated should be preheated to the approximate temperature that it would normally attain during the spraying operation. The distance between the spraying gun and the part is dependent on the process and material being sprayed. Recommendations of the equipment manufacturer should be followed and modified by experience. Speed and feed of spraying should be uniform. The first pass should be applied as quickly as possible. Additional coats may be applied slowly. It is important to maintain uniformity of temperature throughout the part. When there are areas of the part being sprayed where coating is not wanted, the area can be protected by masking it with tape. Relative motion is required. The spray gun may be hand held or mechanically held if the work is moving. This is common practice when building up shafting in a lathe. For larger areas the gun can be hand held or mechanical motion devices may be employed. Recently, robots have been used for thermal spray operations. Figure 9-33 shows the plasma spray system being applied by a robot. Note that the workpiece also rotates.

FIGURE 9-33 Robot spraying operation.

Post Treatment and Safety

Certain sprayed surfaces are given an additional treatment to create fusing. This technique involves a gradual and uniform temperature rise to a fusing temperature of 1850 to 2370 °F (1010 to 1300 °C), depending on the type of alloy being used. Various methods of applying fusing heat can be used. These include the oxyfuel gas torch, a furnace, or induction. Temperature control is required to obtain a good-quality fused coating.

Thermal spraying requires protective clothing, eye and ear protection, and special ventilation. All safety factors with respect to the similar welding process should be observed. Ear protection may be required.

Quality of Coatings

Coatings must be inspected to determine that they are free of cracks, pinholes, blisters, voids, and so on. Coatings over sharp corners, such as keyways, require extra attention. The skill of the operator is a major factor in obtaining good-quality coatings. Written procedures are recommended for each type of application.

9-4 ADHESIVE BONDING

Adhesive bonding (ABD) is a material-joining process in which an adhesive is placed between the faying surfaces. The adhesive solidifies to produce an adhesive bond. The adhesive bond is the attractive forces between an adhesive and the base materials, or substrate. Two principal interactions that contribute to the adhesion are the van der Waals bond and permanent dipole bonds. The *van der Waals bond* is defined as a secondary bond arising from the fluctuating-dipole nature of an atom with all occupied electron shells filled. The *dipole bond* is a pair of equal and opposite forces that hold two atoms together and results from a decrease in energy as two ends are brought closer to one another.

Adhesive bonding of metals, plastics, and composites to themselves and to each other is becoming more and more important. There are no industrial standards for adhesives. They are usually specified by proprietary trade names, which relates to manufacturers' specifications. There are a number of types of adhesives. We are interested primarily in structural adhesives that are capable of withstanding significant loads. However, there are others, such as holding adhesives, that cannot withstand a great deal of force: sealing adhesives used to prevent leakage, lock adhesives used to prevent the loosening of threaded parts, retaining adhesives used to prevent the twisting or sliding of nonthreaded parts, hot-melt adhesives that are applied in the heated state, pressure-sensitive adhesives used on self-sealing envelopes, instant adhesives which cure within seconds, ultraviolet adhesives which cure when exposed to

ultraviolet light, and heat-cured adhesives which require heat to cure. Adhesives can be classified according to their composition or other characteristic. This includes solvent cements, hot melts, silicones, urethanes, epoxies, anaerobics, cyanoacrylates, and acrylics. Each type has its advantages, weaknesses, and specific applications. Selection of the proper adhesive for specific applications is a technical subject beyond the scope of this book.

The advantages of adhesive bonding include the following. The stresses on adhesive-bonded parts are uniform over the entire bonded area, which may allow the use of thinner materials. Materials of all sizes and types can be bonded. If they have different coefficients of expansion, the adhesive bond will compensate since it retains some flexibility. Adhesive bonding has a high resistance to fatigue since it provides a damping action and retains some flexibility. There is no distortion with adhesive bonding since high temperatures are avoided and holes are not used. Properties of metals and other materials being joined are not affected. Adhesives have different characteristics—some may provide electrical insulation, while others will give electrical conduction depending on the design. Adhesive bonds provide seals to prevent leaks. Adhesive bonds eliminate bulges, gaps, projections, or indentations when compared to mechanical fasteners or resistance welds. Adhesive bonding provides cost savings when material thicknesses are reduced or when operations such as drilling or punching are eliminated, or when metal finishing operations can be reduced or eliminated.

There are problems with applications and with service life of adhesive bonding. Different adhesives require different handling and curing treatment. Some adhesives are toxic, some are flammable, some have short shelf life, and so on. Curing of adhesives varies. Some require a long cure time with precise temperature and pressures. Others require ultraviolet radiation. High-temperature service will reduce bond strengths, and some adhesives are sensitive to environmental conditions such as humidity, temperature, and atmosphere. Some adhesives have more than one component, which complicates application.

The properties of adhesive-bonded joints are described differently from metalworking terms. The joints are judged by properties such as peel stress, shear stress distribution, tension and compression stress distribution, and cleavage and peel stress distribution. Testing methods have been established by the American Society for Testing and Materials (ASTM).[7] This includes tests for tensile strength, shear strength, cleavage strength, and peel resistance.

The joint types used for adhesive bonding are the lap/overlap; the joggle lap; the butt joint, which can utilize tongue-and-groove design; the scarf joint; and the strap joint (single or double). The mortice and tenion are used for corner joints (Figure 9-34).

There are certain factors to consider when using adhesive bonding: (1) adhesive selection, (2) surface preparation, (3) application of the adhesive, and (4) curing. The successful performance of an adhesive bond depends on proper control of these four factors. They are equally important; however, the performance of an

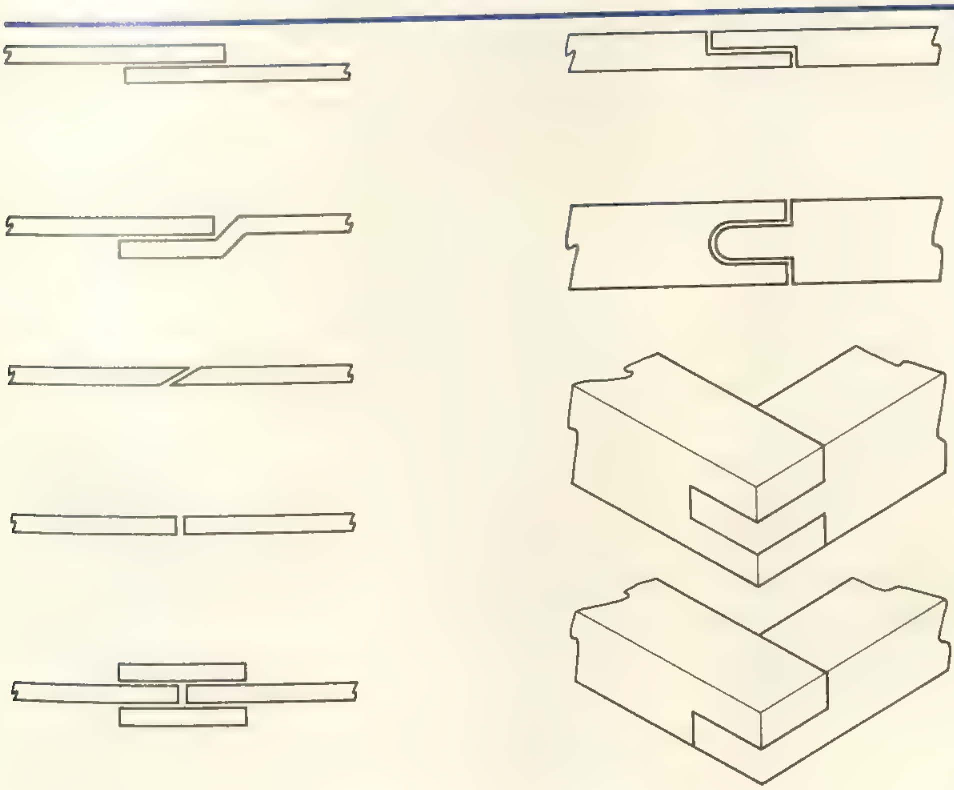


FIGURE 9-34 Joint types used for adhesive bonding.

adhesive depends on surface preparation, and except for the adhesive for oily surfaces, the surface must be clean to produce an efficient joint. Adhesives are normally applied manually; however, recently, robots have been used, particularly in the automotive industry. The application can be a major expense. The application process can range from simple manual to sophisticated robotics and depends on the adhesive. For example, solvent cements may be sprayed on the surface; hot melts require heating applicators. Viscosity, whether thick or thin, dictates the application technique, as does the time and method of curing. There are single, double, or triple component adhesives and catalyst/accelerators.

The cost of different types of adhesives varies considerably and must be considered relative to alternative joining methods. In general, the adhesive that assures the most efficient joining, the least amount of preparation and curing, and requires minimum finishing yet provides the best strength is the proper selection.

Types of Adhesives for Bonding

The most commonly used structural adhesives are the acrylics, epoxies, urethanes, and cyanoacrylates. Each has its own characteristics.

Rubber-Base Adhesives Rubber cements or solvent cements are adhesives that contain organic solvents rather than water. They are based on nitrocellulose or polyvinyl acetate, normally elastromeric products, dispersed in solvent. They are free flowing, thin-set materials that dry to hard, tack-free films. Some others retain a soft, tacky, flexible film. They are used in pressure-sensitive labeling operations, in contact bonding for the woodworking industry, and in laminating applications, such as veneering. Mastic-type adhesives are a solvent cement used in the building and construction industry. They are used to bond wood and drywall to concrete and other vertical surfaces. Rubber and solvent cements can be sprayed or hand applied using a roller. They are usually flammable. The chemistry of the adhesive dictates its characteristics and recommended use.

Resin Adhesives Synthetic resins are composed of synthetic organic materials and are relatively expensive. They are used when a high-quality bond is required, and they are relatively heat and moisture resistant. They can be applied by automatic or semiautomatic equipment, are used for sealing cardboard cartons and for wood, and for vinyl film laminations.

One of the major groups is the hot melts, which are combinations of waxes and resins that form a bond by applying heat and then cooling. Solid hot melt synthetic resin adhesives contain neither water nor solvents and set up quickly. The hot-melt type must be heated to between 250 and 400°F (121 and 204°C) before they are applied. Hot-melt adhesives resist moisture and can be used on nonporous surfaces. They are used for bonding metal to various surfaces. They are used for packaging and in the furniture and woodworking industry.

Epoxy Adhesives The epoxy adhesives can be used to bond metal to metal, metal to plastics, and plastics to plastics. They are a family of materials characterized by reactive epoxy chemical groups on the ends of resin molecules. They consist of two components, a liquid resin and the hardener to convert the liquid resins to solid. They may contain other modifiers to produce specific properties for special applications. Some epoxies will bond to concrete. One of the newer advances is the oily metal epoxy that bonds directly to oily metals "as received" with normal protective films on them. The oily coating need not be removed. Other epoxies can be a one-component type, but these require a heat-cure operation. Epoxies are good surface wetters. They achieve intimate molecular contact with the surface to be bonded and will achieve high adhesion on almost any surface. Epoxies are the most expensive of the adhesives; however, they offer more advantages.

Solvent Joining of Plastics

There are two basic methods of joining plastics by chemical action, the solvent joining method and the adhesive joining method. Solvent joining is applicable to the thermoplastics group of materials, which are readily dissolved in a solvent. Solvent joining cannot be applied to *inert* materials such as polyolefines. In the solvent cementing technique the surfaces to be joined are coated with a solvent and then held together under pressure until the solvent has evaporated to form a seal. Butt, lap, and tongue-and-groove joints are employed. The joint strength is dependent on the material and the joint design. Improved bonds are achieved by using specially developed solvent cements which contain a small quantity of the plastics of the type used in the components to be joined. The solvent cements have an advantage over straight solvent welding since they will fill voids in poorly fitted joints. Adhesive joining of plastics is similar to adhesive joining of metals.

9-5 JOINING PLASTICS

Plastics are being more widely used in the manufacture of more and more products. Plastics are replacing metals when their properties are appropriate, especially where corrosion resistance or weight restrictions are important. They are used for smaller parts or assemblies that are produced in high volume. Pipe and complex formed parts are often joined.

Plastic is defined as "a material that contains as an essential ingredient one or more polymeric substances of high molecular weight. It is solid in its finished state and

at some stages in its manufacturing or processing can be shaped by flow into finished articles."[8] Plastics are organic, man-made materials. Plastic materials have a complex nomenclature based on their chemistry. Many have common names, trade names, or abbreviations, which may lead to confusion. Exact identification is important when working with plastics. Most plastic materials will burn and they have a coefficient of expansion about four times that of steel.

All plastics fall within two categories, which is based on their chemical composition and on their elevated-temperature characteristics. They are classed as either thermoplastic or thermosetting.

Thermoplastic materials have their long chain-like polymer molecules held together by relatively weak van der Waals forces, hydrogen bonds, or the interaction of polar groups. When the plastic is heated, these forces are weakened so that the material becomes soft and flexible. At higher temperatures it becomes a viscous melt and can be molded or extruded into the required final shape. Thermoplastic materials can be repeatedly softened by heat and hardened by cooling. It can readily be welded by the application of heat, making a monolithic structure; fusing occurs across the bond line. Typical thermoplastics are polythylene, polyvinyl chloride, polystyrene, polypropylene nylon, polycarbonate, and acetal.

Thermoset plastics are formed by a chemical reaction. Normally, the reaction occurs above room temperature and under pressure during the molding operation. During molding polymer molecules capable of further reaction are chemically cross-linked into a close network structure. When cooled the resulting product is rigid. If extra heat is applied, the material will degrade. Thus thermoset plastics are not weldable by any method that involves heating. They can be joined by adhesive bonding. See the adhesive bonding section for details. Typical thermoset plastics are phenol-formaldehyde, melamine-formaldehyde, urea-formaldehyde, and epoxies.

The successful use of plastics often requires that parts be joined together securely. Mechanical fasteners can be used; however, for permanent joining a better method is desired. Permanent joining methods fall within two categories: welding and adhesive bonding. Welding produces a monolithic structure. Adhesive bonding does not produce monolithic structure and is covered in another section.

Weldability of Plastics

Weldability of a thermal plastic depends on the welding method being used, the thickness of the materials being joined, and the joint design. There are two basic types of thermal plastics, amorphous and crystalline polymers. The solid-state structure, that is, the manner in which the polymer molecules are arranged, determines its physical properties, melting, and welding characteristics.

Amorphous polymers have no orderly structure. The molecules are randomly arranged. Amorphous plastics do not have a definitely defined melting point. When heated they gradually soften when they pass from a rigid or solid state to a transition into a leathery and then a rubbery state. This is followed by a rubbery flow and then a liquid flow to a true molten state. Solidification is gradual, in the reverse process. The energy requirements remain relatively constant as the temperature changes.

Crystalline polymers have a very orderly molecular structure due to the chemical energy or interaction within each molecule. They can be considered as being like either flat or coiled springs. The higher the degree of crystallinity, the more complete the spring-like structure. Crystalline polymers have a sharp melting point. The plastic remains rigid until it reaches its melting point, and then immediately becomes fluid. As the temperature of the crystalline materials approach the melting point, a higher level of heat energy is required to continue to increase the temperature. Solidification occurs just as rapidly as melting, due to the sudden release of energy as chemical interaction or crystalization of the molecules takes place. In general, amorphorous thermal plastics are easier to weld than the crystalline forms.

There are five steps to the thermal welding of thermoplastics.

1. Surface preparation
2. Heating
3. Application of pressure
4. Diffusion or welding
5. Cooling

Surface preparation is important since many molded plastics have a contaminated surface layer known as a mold release. This must be removed and for certain processes the abutting surfaces must be absolutely flat for intimate contact. Heating is accomplished by different methods and is the basis for identifying the many plastic welding methods.

The application of pressure is done in different ways. It can be done manually, in presses, or in automatic fixtures. It is often combined with tooling, which may include part of the heating apparatus as well as the pressure method.

Diffusion occurs once the liquid-to-liquid interface has been established. Diffusion occurs almost instantaneously with crystalline or semicrystalline materials. For amorphous materials heated only slightly above the melting point, diffusion takes longer.

The final step in making the weld is to cool the assembly and resolidify the joint. The load or pressure

must be maintained until the resin has sufficient strength and stiffness to support the total weldment.

Welding Methods

There are a number of different welding methods.[9] They all require the use of heat; thus all of them can be called "thermal joining" methods. The heat for welding is produced in different ways. The heating method identifies the different welding/sealing/bonding methods:

- Electromagnetic (or induction)
- Friction (spin welding)
- Heated surface (heated tool/hot plate)
- High frequency (dielectric heating)
- Hot gas
- Implant
- Radiant
- Ultrasonic (sonic)
- Vibration

Electromagnetic Welding The electromagnetic bonding or magnetic heat sealing method uses induction heating for creating the weld. Induction heating utilizes high-frequency alternating current, which creates heat in magnetic particles placed in its field. In electromagnetic plastic welding, micron-sized magnetic particles are dispersed within a thermal plastic matrix. When this material is placed between the faying surfaces to be welded and exposed to the electromagnetic field, heat develops at the interface, causing melting and subsequent fusion of thermal plastic materials. It produces a polymer-to-polymer linkage between all compatible thermal plastics. It can be applied in hot melts or solvent binder systems, or as implants in the joint. Equipment required is a high-frequency power source from 2 to 20 kW output with a frequency of 3 to 30 mHz; 2.5 to 3.5 mHz is most often used. Work coils, usually water-cooled cooper coils, produce the magnetic field in the workpiece. They can be incorporated into the fixtures. They can be used on thick or thin sections, irregular shapes, and with the right vehicle can be used to fill voids in the joints. They can be automated and are used to join plastics that are normally difficult to weld. They are relatively fast and are used for production applications.

Friction Welding Friction welding, sometimes called spin welding, uses heat that is developed at the interface of the parts being welded due to friction. The weld is made by holding one piece stationary and rotating the other piece against it under pressure. The rotating member is stopped as soon as melting occurs and the weld is consolidated under pressure while it cools. The typical joint strength on like plastics is 90% of the strength of the material. Strength is largely dependent on the joint area. Welding time is from 1 to 5 seconds. The method can be used to produce welds in similar and dissimilar plastic materials. Equipment is similar to that used for metals except that it is lighter in design and construction. Friction welding is rapid and an efficient joining technique that can be applied to most thermal plastics. The major disadvantage is that it can be used only on components (at least one component) having a circular cross section.

Heated Surface Welding Heated surface, sometimes called heated tool, hot plate, or heated bar welding, uses heat that is generated in the hot tool. Electrical resistance heating coils are normally used to heat the tool or bar. There are two variations. One is used for sealing plastic films or thin material, and the other is for joining heavier pieces.

When joining thin materials the parts are held together under pressure and heat is applied for a short period to produce the weld. There are several variations, one known as impulse heat sealing, which uses the pressure bars but has a resistance heating element covered by fiberglass. A pair of bars produce pressure on the pieces being joined; short impulses of electric current provide the heating to complete the weld. Another variation uses circular bars, or wheels, which are heated and rotate and traverse the joint, providing heat and pressure. Circular bands are also used, but in all cases the bonding is accomplished by the direct application of heat.

For heavy materials, this technique requires that the two faces to be joined be flat. These two faces of the parts are held against a heated metal surface. When the plastic surface begins to melt the heated metal plate is removed and the pieces are quickly brought together and held under pressure. In this application a flash or reinforcement occurs at the joint. Both of these methods can be automated and programmed.

The hot plate method is widely used for plastic pipe welding for field installations. It is used for making butt welds and for branch joints. Portable semiautomatic equipment is used in the field (Figure 9-35).

High-Frequency Welding High-frequency sealing or bonding uses heat produced by dielectric heating. Dielectric heating occurs in insulating materials that possess electric dipole moments and exhibit polarization in a high-frequency electric field. Polarization and molecular agitation of the material creates heat. Nonresponsive materials can be bonded by using a film or coating between the two parts to be bonded, which generates the heat in the magnetic field. High-frequency generators with outputs up to 50 kW are used, with a frequency of 27.12 mHz. This frequency is used to avoid radio interference with communications. The power is programmed and this method is used primarily in automated systems, which may include a press or pressure-applying device. Special dies are often used, which may also emboss the joining

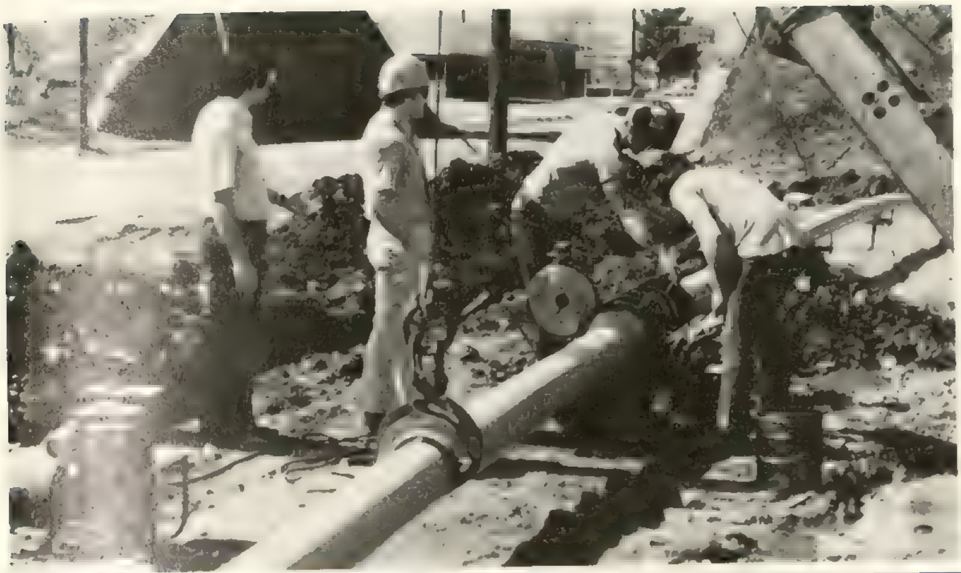


FIGURE 9-35 Field welding plastic pipe.

material. In some applications roll-type tooling is used to make a continuous weld.

Hot Gas Welding The hot gas welding method utilizes the heat transmitted by hot gases to melt the surface to be joined and also to melt a plastic welding rod to fill joint grooves. The apparatus for producing the hot gas is a torch, which normally uses resistance heating coils to heat the gas, which is directed to the welding area. It is used in the same manner as an oxyacetylene torch for welding metals.[10] Compressed air is most often used as the heated gas; however, nitrogen, or in some cases argon, is used to help eliminate problems associated with oxidation. Hot gas welding is normally a manual operation utilizing two hands. Manipulative skill is required. The hot gas welding method is used to produce large fabrications made of sheet materials. An example is ducting work, pipe work, and ventilator hoods for exhaust systems handling corrosive gases. The apparatus used to produce hot gas welding is relatively inexpensive, consisting of a hot gas torch, gas regulator, an air compressor when required, and the plastic filler rod.

The parts to be joined are beveled along the edges to provide a groove for filler material from the welding rod. The welding rod is of the same composition as the parts being welded; it is usually round and smaller than the groove. Multiple passes may be used. The plastic welding rod is not fluid, but semifluid, and fairly easy to control. The application of hot gas welding is shown in Figure 9-36.

Implant Welding Implant welding utilizes heat generated by a metal implant or insert in or adjacent to the weld joint. There are two basic variations. One uses a molded-in resistance wire which produces heat when it is connected to a source of electric power. The other category utilizes a metal insert which is heated by induction via electromagnetic radiation. Both methods produce high-strength, high-quality welds in a variety of thermal plastic materials.

The best known application of hot wire welding is the joining of pipe to fittings. The electric resistance wire is molded into the fitting. Heat is produced by the resistance of the wire to electricity provided by a special power source usually operating at 24 V dc. Pressure is accom-

FIGURE 9-36 Hot gas welding plastic assembly.

plished by the thermal expansion of the part that is heated. The disadvantage is the extra cost of the molded-in resistance wire which remains in the joint. This process is commonly used for field welding of thermal plastic pipe.

The other variation, metal insert welding, utilizes induction heating of the metal insert. This could be considered electromagnetic welding, but it does require that the implant use electromagnetic power, which generates heat in the implant, which is placed at the interface of the parts to be joined. The implant can be a piece of iron or steel or iron or stainless steel filings in a matrix. Screening is sometimes used. The high-frequency power source used to create the heat is similar to the equipment used for electromagnetic welding. During the heating period, pressure is applied to the joint. This method can be readily automated with the power source programmed. A successful application is the plastic membrane seal in bottle caps. In this case the metal component is a part of the product, and the welding occurs where the plastic membrane is in contact with the metal.

Radiant Welding Radiant welding uses heat from an infrared heating source or from a laser beam. In either case, heating is due to electromagnetic waves being absorbed by the material surface. The weld surfaces are exposed to infrared lamps or to a laser, and are heated to melt the thermal plastic. When the thermal plastic is molten, the parts are pressed together until the material has cooled. This method is usually automated, and accurate dies are used to press the parts together and maintain dimensional accuracy. This process is rather critical from a time point of view and has not been extremely successful.

Ultrasonic Welding Ultrasonic welding, sometimes called sonic welding, uses heat that is generated by vibration between the parts, causing the two surfaces to move relative to each other. This causes a temperature rise as mechanical energy is converted to heat. The heat generated is sufficiently high to melt the surfaces in contact. Pressure is required to hold the parts together during the welding operation. The workpieces transmit the ultrasonic vibration to the interface. The contact area with the sonic probe of the welding machine does not rise in temperature and there is no marking. Frequencies of 20 to 30 kHz are used. Equipment consists of a power source and frequency converter and a piezoelectric crystal which converts the electrical energy to mechanical energy in the form of vibrations. The frequency of 20 kHz is above the audible range for most people. Weld cycle time is very short, usually on the order of 1 to 2 seconds. Most thermal plastics can be joined by ultrasonics and the rigid plastics are the most easy to weld. Materials with a low modulus of elasticity attenuate vibrations and are more difficult to weld. Dissimilar plastics can be welded if their weld points are similar and there is chemical compatibility. Ultrasonic welding of plastic parts is shown in Figure 9-37.

Vibration Welding Vibration welding uses heat that is generated by relative linear motion between the parts being welded, which are held together under pressure. The magnitude of movement is from $\frac{1}{16}$ in. (1.6 mm) to $\frac{1}{4}$ in. (3 mm). The frequency of movement is on the order of 100 to 300 Hz. This method is very similar to friction welding and is sometimes called linear friction welding. As soon as the generated heat causes melting of the surfaces at the interface, the vibration is stopped and the parts are aligned in final position and pressure is applied. Welding time ranges from 2 to 3 seconds, with a 1-second holding time for the joint to solidify. It can be used to weld most thermal plastic materials. It will weld numerous complex shapes together simultaneously. The equipment is designed especially for this welding and can be automated.

FIGURE 9-37 Ultrasonic welding of plastic parts.

9-6 JOINING COMPOSITES AND CERAMICS

Composites are being used more and more by the automotive industry and by the aircraft industry. A composite material is composed of a combination of two or more constituents differing in forms that are essentially insoluble in each other. Generally, they combine high-strength reinforcing material, which is normally in a fiber

form, and a holding material, or matrix. They offer certain advantages over metals and are replacing metals for some applications. The basic advantage of composites over metals is their high strength-to-weight ratio, their corrosion resistance, and the fact that they can be made either nonconductive or conductive to electrical current. They offer design flexibility, reduced finishing costs, ease of parts assembly, and can be fabricated with less expensive tooling.[11]

Composites have certain disadvantages; in general, they are more expensive than the metals they replace. They are difficult to join together and certain types have specific disadvantages; some are flammable, others do not have high-temperature properties, and so on. Even so, it is becoming necessary to join composites to make larger assemblies.

There are basically three categories of composites:

1. Polymer–matrix composites (plastics)
2. Metal–matrix composites (MMC) (metals)
3. Ceramic–matrix composites (ceramics)

The most advanced types are the polymer–matrix composites, which have been in use for many years and are finding wider applications. The least advanced are the ceramic–matrix composites, which are just now in the research laboratories but will find industrial uses in the future. The metal–matrix composites (MMC) are currently being used; however, their price has prohibited widespread acceptance at this time.

Composites are identified by the materials they contain, normally two. An example would be boron–aluminum, where boron fibers are in an aluminum matrix. The specification for a composite would include the names of the two components and a percentage of reinforcing materials by volume in the total composite. Normally, the reinforcing materials range from 10 to 60%. Often, the specification would include the analysis of the matrix and its treatment, such as heat treatment, and the type of reinforcement and its form. The reinforcing materials used in composites are either continuous or discontinuous. The continuous type would be wires or fibers which would be drawn, extruded, or spun. The discontinuous type would be chopped wires or fibers, whiskers, or particles. The reinforcing materials affect the engineering performance of the composite. It is important to know the orientation, length, shape, and composition of these materials. The matrix has two functions: (1) to hold the reinforcing materials or filaments in place; (2) as it deforms, it distributes the stress through the reinforcing materials. The matrix must be more ductile than the reinforcing material. It must transmit the forces to the reinforcing materials; thus there must be an intimate bond between the reinforcing material and the matrix. Joining composites depends entirely on the type of composite.

The polymer–matrix composites are joined by mechanical fasteners, adhesives, and if the polymer matrix is a thermoplastic material, by welding.[12] For welding they are treated the same as a plastic material, based on the composition of the matrix. High-strength carbon fiber polymer composites can be joined by using resistance heating of the carbon filaments and pressure. Another system for producing lap welds is use of induction heating with a wire screen placed between the faying surfaces. An induction heating system introduces magnetic flux through the plastic to the wire screen, which becomes heated and creates melting of the surface and by means of pressure produces a weld. Fairly low power at a high frequency is used. Embedded resistance wires can also be used as well as ultrasonic and friction welding. See the section on plastic welding for details.

The metal–matrix composites (MMC) have the appearance of metals and are considered weldable with some of the welding processes. Welds have been made successfully using the gas tungsten arc welding process on titanium composites with metal reinforcing wires. Aluminum–boron composites have also been welded with gas tungsten arc welding. There can be severe damage to the boron filaments if the heat input is not accurately controlled. Research is ongoing. The plasma arc and electron beam processes are not acceptable since they usually cause melting of the boron filaments and result in metallurgical reactions which decrease the strength of the joints. Resistance welding, particularly spot welding, has been used for lap welding aluminum–boron composites. Resistance brazing has been used successfully, as well as weld bonding. Brazing and diffusion welding have also been applied successfully to the joining of metal–matrix composites. Ceramic–matrix composites are treated in the same way as ceramic materials.

Ceramics

Ceramic materials have been around for many, many years. They are commonly thought of as clay products made into dishes. Recently, engineered ceramic products have been considered for many applications, due to their high-temperature properties, low density, thermal insulation, wear characteristics, and corrosion resistance. Engineered ceramic products are made of high-purity raw materials so that their properties are consistent. Widespread use of ceramics will require that they be joined together to metals and to nonmetals.

There are many different types of engineered ceramics. They fall into three general categories and are based on nitrides, carbides, and oxides. The two most widely used nitrides are silicone nitride and aluminum nitride. The most common oxides are alumina and zirconia. The most popular carbides are silicone carbide and boron carbide.

Ceramics are currently used by the aerospace in-

dustry, primarily in jet engines, the automotive industry, and the electronics industry. Much more use is planned as ceramic products are improved, have more consistent properties, and as additional data are acquired. Ceramics can be joined by means of adhesives and by means of cement-mortar-type inner layers. Unfortunately, adhesives do not have high-temperature properties, thus are limited to medium-temperature applications. Cement and mortar have higher-temperature capabilities but do not provide sufficient tensile strength for many applications. Fusion welding has not been applied successfully to joining ceramics. Successful joining has been accomplished with the use of metallic inner layers. The joining process usually involves brazing, soldering, or diffusion bonding. The inner layers are usually ductile metal foils placed between the parts to be joined. High-quality joints have been produced with metallic interlayers using the diffusion bonding procedure. The joining of ceramics to metals has been more successful. Mechanical joints are widely used. This is the familiar method of manufacturing spark plugs, which is done by crimping the metallic portion around the ceramic portion of the spark plug. Adhesive bonding has also been used and has many applications; however, it is severely limited due to the lack of high-temperature properties.

The joining of ceramics to metals seems best when a metallic interliner is used. Interliner metal must be selected so that it will "wet" both the metal and the ceramic and should have a melting temperature close to that of the metal. The diffusion bonding technique seems to be the most successful, and with a voltage applied across the joint, the bonding seems even more successful. Silicone nitride has been joined to various metals using a copper–titanium intermetallic or filler alloy. One of the major problems with joining ceramics to metals is their difference of thermal expansion, which limits the possibilities. The intermetallic layer seems to be an assist in this regard, such as a titanium layer of filler metal in austinetic stainless steel. Much research, and ultimately better solutions, will become available.

9-7 HEAT FORMING AND STRAIGHTENING

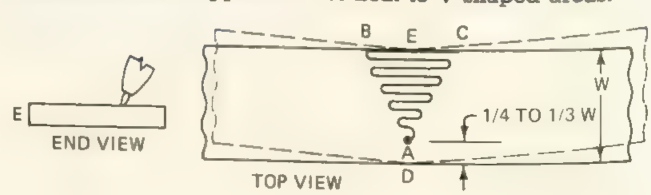
Heat, normally applied by the oxyacetylene torch, can be used to bend or straighten metal sections or parts. To best understand heat forming and straightening, the reader should read "Welding Distortion and Warpage" in Chapter 23.

All metals expand when heated and contract when cooled. The amount of expansion depends on the temperature increase, the coefficient of expansion of the metal heated, and size of the heated area. Unrestrained metal expands in all three directions, but metal is normally restrained due to unequal heating. Heat causes plastic deformation or upsetting during heating. This creates dimension changes upon cooling. The strength of metal decreases rapidly as the temperature of the metal is increased. A thorough understanding of these factors will make it obvious why distortion occurs on weldments. Distortion occurs as a result of forces created by differential heating. These same forces can be used to bend or to straighten metal pieces.[13] This principle was put to practical use by Joseph Holt in the late 1930s and perfected by his son, Richard Holt, in the late 1960s.

Flame bending, or heat forming and straightening, is the application of these same principles. It can be used to correct distortion that may occur from welding or from accidents. To understand the application of heat to bend or straighten members, we start with a relatively simple example. Consider a flat bar approximately ¼ in. (6.4 mm) thick by 2 in. (50 mm) wide and approximately 24 in. (650 mm) long. Heat with an oxyacetylene welding torch using a medium-size single-orifice tip. Adjust the torch for a neutral flame. Before beginning the heat pattern use a piece of chalk and mark a triangular area from point *A* located one-fourth of the width of the bar toward edge *D* and mark a pie-shaped or V-shaped area to points *B* and *C* on the *E* edge of the bar (Figure 9-38). The angle formed by *B, C* to *A*, should be approximately 60°. Begin the heating at point *A* with the flame pointed slightly toward edge *E*. Hold the flame steady until point *A* becomes heated to a light red (1110°F, 593°C). Be careful not to melt the surface of the bar at any time. When spot *A* has reached a light red color, start to move the torch as shown in the figure. Move the torch slowly in a zigzag fashion, bringing it up to the same light red temperature. Continue traveling, making sure that the part comes up to temperature before moving farther toward the far edge *E*. Continue the zigzag line of travel until you have reached points *B* and *C* on edge *E*. This will produce a V-shaped section that has been heated progressively from near edge *D* to edge *E*. Cooling will also be progressive in the same direction. After the bar has cooled it will take the shape shown by the dashed lines.

The mechanism for creating this action is based on the principles mentioned above. The heat at point *A* causes the metal to expand in all three directions; however, it is restrained by the adjacent cold metal and it will therefore upset or become slightly thicker. The localized heating continues as the flame is moved from point *A* toward *B* and *C*. The heated area is increased

FIGURE 9-38 Application of heat to V-shaped areas.



as the flame moves away from point A. The metal at point A begins to cool and contract as the temperature falls. Normally, points B and C are reached before the temperature at point A cools appreciably. The widened heated area and the contracting metal behind it create the forces that cause the bending. Do not heat the metal at point D or beyond point A on edge D. As the cooling continues from point A towards edge E, the metal contracts. There is more metal to contract as the heated area becomes wider. This contributes to creating more motion or bending as cooling continues. Point D acts as the hinge pin; the material between B and C contracts the most. The amount of distortion with all factors equal is dependent on the angle between B and C. For less action use a sharper angle in the order of 45° or for less movement reduce it to 30°.

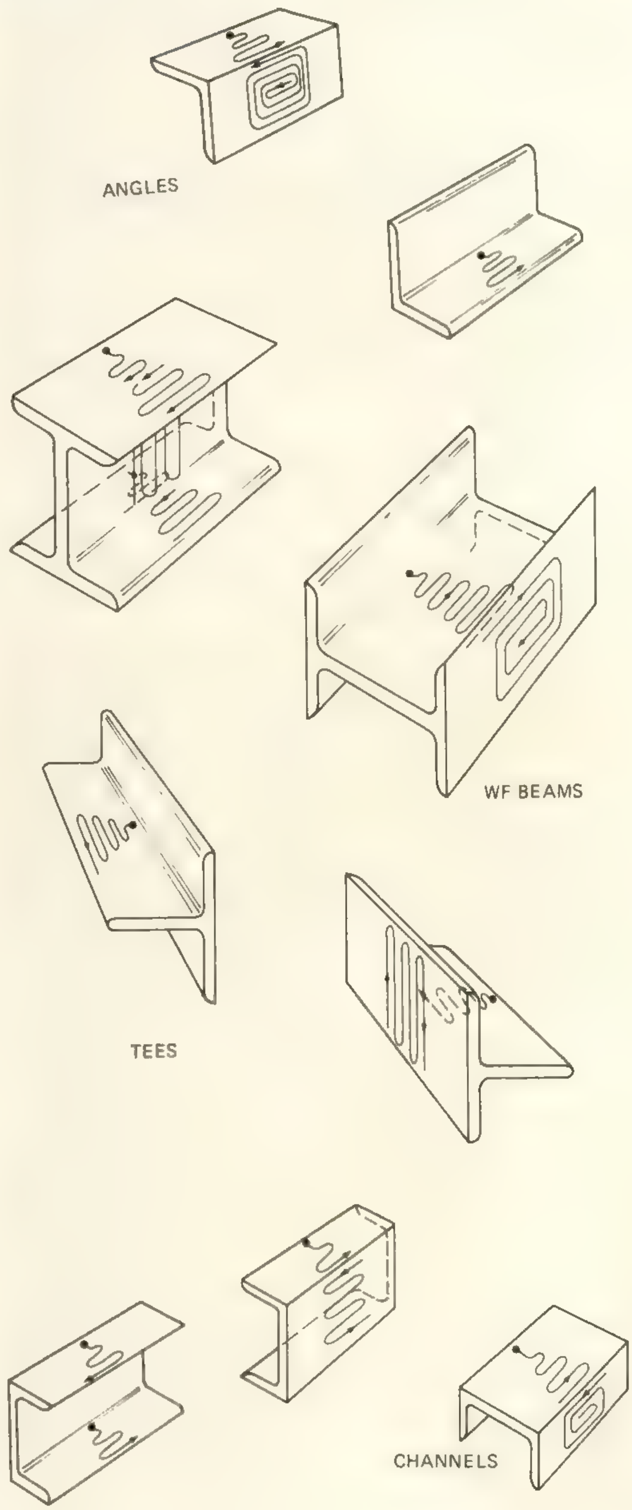
If more motion is required, additional heated V's can be made adjacent to the first one. It is possible by this method to create a ring out of a straight bar. This requires many applications of heat but it has been done.

The same application of V-shaped heating areas can be used to bend or straighten other types of structural shapes. Figure 9-39 shows the heat application that can be used for other shapes. The large end of the V will be the portion where the maximum contraction occurs. The amount of contraction can actually be calculated; however, since temperature control is not precise, the amount of metal heated is not exactly known due to conduction of heat to the cooler areas. Formulas have been worked out and are available. The best method of understanding the amount required for shrinkage is by experience.

When straightening shapes other than flat bars, it is necessary to consider the relationship between webs and flanges. For example, in the figure the rolled angle can be bent with the vertical leg acting as the hinge point. All the heating is done on the horizontal leg. If, however, the vertical leg of the angle must be shortened it should be done with thorough heating of the vertical leg when the wide portion of the V comes to that leg. Progressive heating should not be done in the vertical leg. Progressive heating is used only when a V-shaped area is to be heated. By closely following the figure an angle can be bent in either direction. The same applies to channels, T's, and I or wide-flange beams. The basic principles can also be used for box sections and pipe. In all cases, the starting point should be approximately one-fourth of the distance from the edge that is to be the hinge point.

The same technique can be used to correct warpage of structures that involve T-type joining utilizing double fillet welds. In this case, the application of heat is linear rather than V-shaped. Warpage is often encountered when fillet welds and double fillets are made on one side of a member forming a T-joint. Applying the torch flame to the center of the top of the T will create shrinkage in this point, which will tend to bring the top of the T back

FIGURE 9-39 Application of heat to bend rolled shapes.



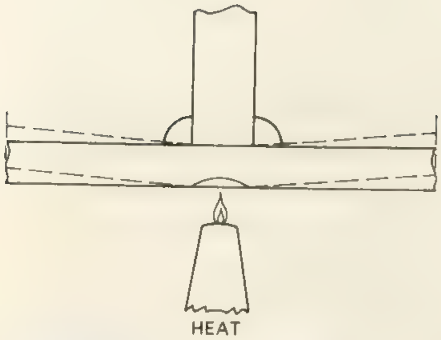


FIGURE 9-40 Application of heat to correct warpage.

into a flat plane (Figure 9-40). The same technique of straight-line heat application can be used to shorten parts.

Diaphragms, bulkheads, or flat plates in welded assemblies may sometimes buckle as a result of weld distortion. One method of reducing this buckling is to create round heated areas approximately 3 in. (75 mm) in diameter across the surface of the buckled plate. Each individual heated spot will upset and as it cools will create shrinkage in all directions. By adding enough of these round heated spots the buckling can be completely eliminated from the flat plate.

The technique of heat flame straightening and bending can be used to salvage members damaged by accident. It has been successfully applied to structural work of bridges, of large buildings such as aircraft hangars, and of offshore drilling platforms. In these cases, special precautions must be exercised. Force is sometimes applied to assist the heat-forming operation. A careful analysis must be made before attempting such jobs and it must be determined whether the part being straightened is stressed in tension or in compression. When the temperature of the member is increased by flame heating, its strength is greatly decreased. In order to create shrinkage action, it is necessary to have the member loaded in compression. This will assist upsetting and will help create the favorable direction of warpage to straighten the member. If the member is stressed in tension, compression loading should be added, by means of temporary bracing, to accomplish the heat-straightening operation.

The flame bending system is also used for creating camber in beams. Samples of wide-flange beams formed to large radiuses for roof structures are given by reference 14. Here wide-flange beams 80 ft (24 m) long and 24 in. (288 mm) wide were formed to curvatures of 135 ft (41.1 m). These were erected and became the arch of a gymnasium. With skill and experience this type of heat forming can be very precise.

There are certain precautions that should be taken in heat forming or bending. It is used on low-carbon steels. It should not be performed on medium- or high-carbon or quenched and tempered steels. Precautions should be used in cooling the heated zones. Air quenching or water cooling can be used. This will not appreciably increase the amount of distortion. It will merely decrease the time for the shrinkage action to take place. When steel with high-carbon content is quenched rapidly, it will harden, which can be detrimental to service life.

To avoid damage of the steel, it is recommended that 1200°F (649°C) is the maximum temperature utilized. This temperature produces a dark red color on steel in a subdued light. It has been found that heating the same spot does not adversely affect the steel, provided that it is not heated to temperatures above 1200°F (649°C). Heat forming can be used on stainless steels and on aluminum. For stainless steels the maximum temperature should be 800°F (427°C) and for aluminum the maximum temperature should be 400°F (204°C).

For thicker materials, larger torch sizes are required. For extremely heavy materials, multiorifice torches can be used. It is important to maintain the maximum heat differential between the heated area and the adjacent cool area. This provides for more movement during the cooling period.

In straightening materials in two dimensions, it must be remembered that the torch side of the part being heated will be heated to a higher temperature than the underside. For this reason, the torch side will normally have greater reaction than the underside. Thorough heating is required and in many times it is possible to judge the heating by noting the color on the underside. With sufficient practice and experience some rather amazing feats can be done utilizing the oxyacetylene torch for heat forming and straightening.

9-8 PREHEAT AND POSTHEAT TREATMENT

Preheating is the application of heat to the base metal immediately before welding, brazing, soldering, or cutting, and postheating is the application of heat to an assembly after welding. This might be better described as a postweld heat treatment, which includes any heat treatment following welding.

All the arc welding processes and many of the other welding processes use a high-temperature heat source. A steep temperature differential occurs between the localized heat source and the cool base metal. This temperature difference causes differential thermal expansion and contraction and high stresses. By reducing the temperature differential, these problems can be minimized. This will reduce the danger of weld cracking, reduce the maximum hardness, minimize shrinkage stresses, lessen distortion and help gases—particularly hydrogen—escape from the metal. Preheating will reduce the temperature differential. Preheating increases the

ability of a weld to withstand service conditions largely because of the reduction of the problems mentioned above. Preheating is also done on highly conductive metals in order to maintain sufficient heat at the weld area. The preheat temperature depends on many factors, such as the composition and mass of the base metal, the ambient temperature, and the welding procedure.

The interpass temperature should also be considered. It is involved in multiple-pass welds and is the temperature, both minimum and maximum, of the deposited weld metal and adjacent base metal before the next pass is started. Usually, the minimum interpass temperature will be the same as the preheat temperature. The weldment temperature should never be allowed to become lower than the preheat or the interpass temperature. If welding is interrupted for any reason, the interpass temperature must be attained before welding is started again. Preheat and interpass temperatures must be completely through the thickness of the area of the weld. The interpass temperature may also be specified as a maximum temperature. When welds are made on a small weldment, its temperature will usually increase due to the heat input from welding. Under certain conditions it is not desirable to allow this heat to build up and exceed a specific temperature; therefore, a maximum interpass temperature will be specified. When heat buildup becomes excessive, the weldment must be allowed to cool, but not below the minimum interpass temperature. The temperature of the welding area must be maintained within the minimum and maximum interpass temperature.

There are many different ways for preheating, including use of gas torches, gas burners, heat-treating furnaces, electrical resistance heaters, low-frequency induction heating, and temporary furnaces. The choice of the preheating method depends on many factors, such as the preheat temperature, the length of preheating time, the size and shape of the parts, and whether it is one-of-a-kind or a continuous-production type operation. Any method used for postheating can also be used for preheating.

On critical work the preheat temperature must be precisely controlled. In these cases, controllable heating systems are used, and thermocouples are attached directly to the part being heated. The thermocouple will measure the exact temperature of the part and will provide a signal to a controller, which regulates the fuel or electrical power required for heating. Thus the temperature of the part being heated can be held to close limits. Most code work requires precise heat temperature control.

A common method of preheating is by torches or burners utilizing flames. Figure 9-41 shows a natural gas burner used to preheat the lip of a power shovel dipper. This subassembly is a critical part made of quenched and tempered high-alloy steel. The preheat and interpass temperature must be maintained throughout the entire welding cycle. Open flames such as this cannot be as precisely controlled as other methods and are therefore used only for preheating and maintaining interpass heat.

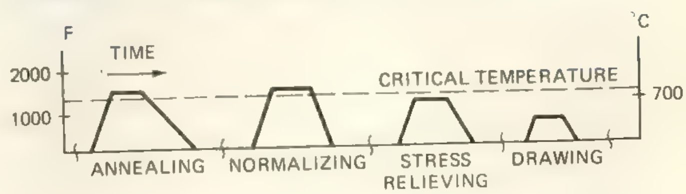
FIGURE 9–41 Preheating with open gas flame.

Postweld Heating

There are a number of postweld heat treatments for weldments but stress relieving is the most widely used. Some of these other heat treatments are annealing, normalizing, drawing, and fusing. *Annealing*, or *full annealing* as it is sometimes called, is a heat treatment that increases the temperature of steel above the critical or recrystallization temperature followed by slow cooling. It is normally heated to a point about 100 °F (38 °C) above the critical temperature line of the steel. Cooling is usually done in a furnace to provide a substantially stress-free condition. Figure 9-42 shows this in diagrams.

Normalizing is similar to annealing. The heating rate and holding periods are identical but in normalizing the cooling rate is faster and is usually done by allowing the part to cool in still air rather than in the furnace. Due to the higher cooling rate normalizing usually provides a structure with greater strength and less ductility than annealing.

FIGURE 9–42 Heat-treatment cycles.



Tempering is a heat treatment done at a much lower temperature than annealing, normalizing, or stress relieving. It is an operation that often follows a quenching operation. It tends to reduce the hardness, the strength of a steel, but it improves ductility and toughness.

Fusing is a specialized process of heating a thermal spray deposit to cause it to coalesce, solidify, and bond metallurgically to the base material. This can be done by almost any heating method.

Stress relieving is of major importance to weldments. It is similar to normalizing except that it is done at a temperature below the critical temperature, usually in the range 1050 to 1200°F (566 to 649°C).

Both annealing and normalizing relieve residual stresses better than stress relieving. They are carried out above the critical temperature. They involve changes in grain structure and tend to produce heavy scale. They may also produce serious dimensional changes, and require that complex large structures are braced to avoid sagging.

Stress relieving is required by some codes. Refer to the specific portion of the code that is applicable, to decide on the stress-relieving schedule. Many products not built under code are stress relieved for some of the following reasons:

1. To reduce the residual stresses inherent to any weldment, casting, or forging
2. To improve the resistance to corrosion and caustic embrittlement
3. To improve the dimensional stability of the weldment during machining operations
4. To improve the service life of the weldment

Stress relieving should be performed if a weldment is subjected to impact loading or to low temperature service, or if it is exposed to repetitive or fatigue loading. In all the heat treatments, heating rates and times may be specified. The maximum temperature is related to the composition of the steel; the holding time, at the maximum temperature, is related to the material thickness; and the cooling rate is related to the particular treatment and to the code. The rate of heating is usually in the 300 to 350°F (149 to 177°C) per hour rate. The holding temperature is usually 1 hour for each inch of maximum thickness in order to provide for uniform heating throughout. The cooling rate is also in the range 300 to 350°F (149 to 177°C) per hour down to a specific temperature. In some cases the cooling rate can be increased when the part has cooled to 500 to 600°F (260 to 316°C). These rates of heating, holding, and cooling are usually a part of the specification and must be followed explicitly.

Temperature indicators and controlling equipment must be used for postweld heat treatment. Figure 9-43 shows a typical car bottom furnace loaded with weldments that have been stress relieved. These furnaces are usually natural gas or fuel oil fired. The complete heat treating cycle may require up to 24 hours. Thermocouples are attached to the weldment and are used to signal the

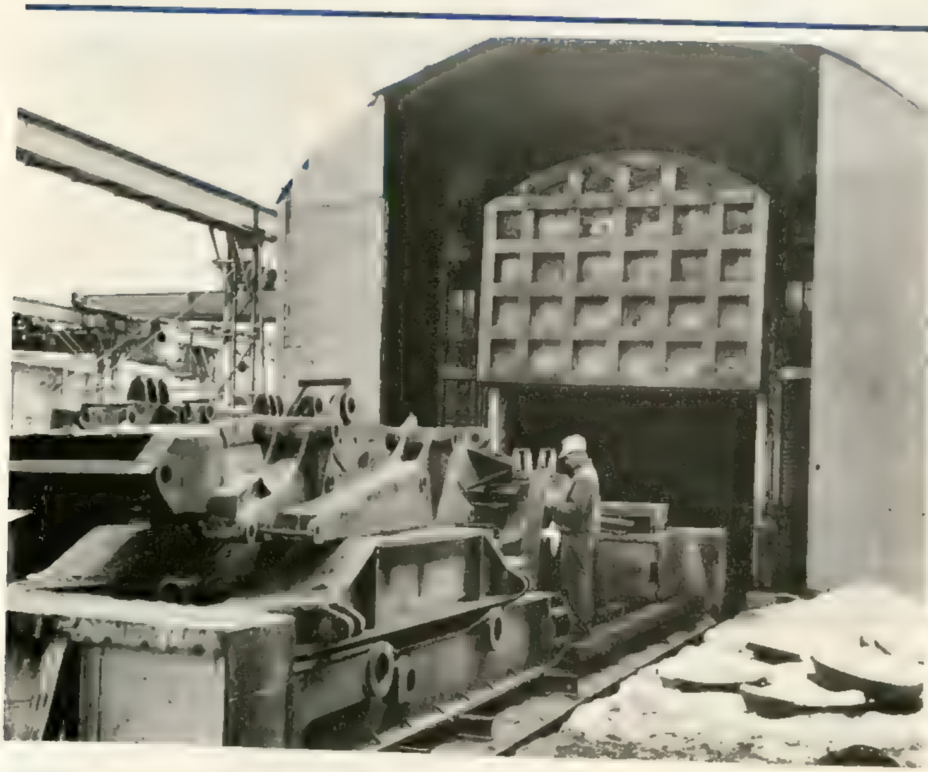


FIGURE 9-43 Car bottom furnace for stress relieving

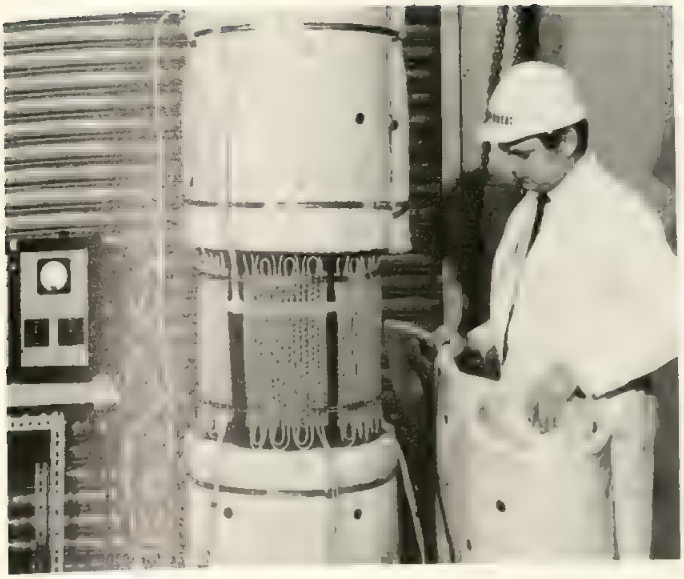


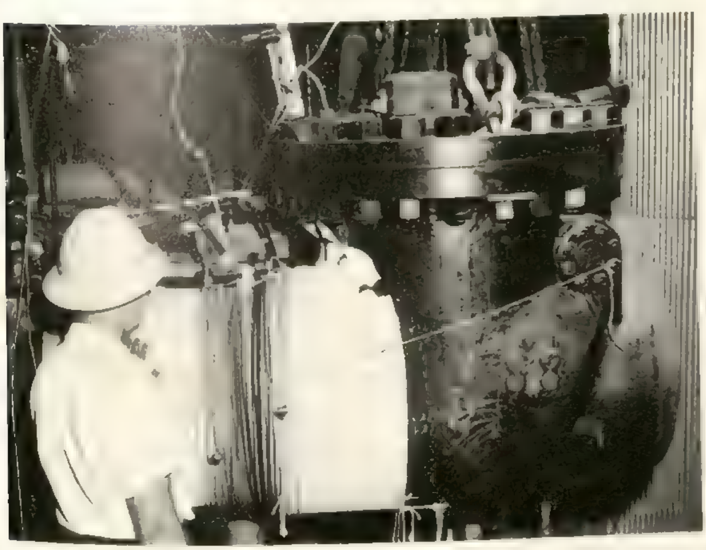
FIGURE 9-44 Resistance heating for pre- and postheat.

controller. Automatic controllers can be set for a specific rate of heating, a specific holding time, and a specific rate of cooling.

Accurate control is also possible with induction and resistance heating. Figure 9-44 shows the use of resistance heating coils for both pre- and postheating. Figure 9-45 shows the use of low-frequency induction heating coils (400 Hz) for pre- and postheating welds made on large pipe. Both resistance and induction heating are very popular for preheating and stress-relieving weld joints in power plant piping welds. Temperature record charts are required by some codes for each weld or weldment.

Temperature measurement for preheating can be done by the use of indicating instruments or by temperature-indicating paints and crayons. The temperature-indicating crayons, which melt at specific temperatures, are widely used.

FIGURE 9-45 Induction heating for pre- and postheat.



A field method for preheating and stress-relieving pipe weld joints has recently been introduced. This method utilizes exothermic material, which is fitted around the welded pipe joint. An insulating nonflammable material is placed between the metal and the exothermic material. This is followed by another layer of insulating material, which is secured to hold the exothermic material in place. The exothermic material is then ignited by a torch or fuse. It burns, creates heat, and heat treats the pipe joint. Temperatures can be checked by means of temperature-measuring crayons, and the results of the heat treatment are checked by making hardness measurements after the heat treatment. This is acceptable by certain codes. The advantage of this system is that additional electric power and skilled personnel are not required.

9-9 MECHANICAL STRESS RELIEF

Thermal stress relief as described in the preceding section is used to relieve yield point stresses inherent in weldments. When thermal stress relieving is impractical or undesirable, mechanical stress relieving can be used. There are three basic types of mechanical stress relieving:

1. Total or local overstressing causing plastic deformation
2. Mechanical vibrations
3. Local surface treatment by hammering or shot peening

All three methods are used successfully and each has specific application advantages and disadvantages. The overstressing method can be accomplished in different ways. The objective is to load or stress the weldment beyond the yield point stress of the metal and cause plastic deformation. Overstressing loads can be applied slowly or rapidly. When the load is removed, the maximum stresses remaining will be below yield point and under certain conditions may become residual compressive stresses. One way of accomplishing this is by proof testing the weldment with 150 to 200% of the maximum load. This will reduce the yield point stresses when the load is eliminated. Another method of overstressing is to thermally expand the metal adjacent to the weld. This is done by means of traveling gas heating torches. The expansion overstresses the weld in the heat-affected zone, which reduces yield point stresses. This thermal method is used to reduce residual stresses in welded ships.

Peening the weld surface by hammering or by shot blasting plastically deforms the surface, which reduces yield point stresses. This technique can provide surface compression stresses and is widely used to increase fatigue life. The peening and hammering is difficult to control but is widely used for local stress relieving.

Stress relieving by exposure to mechanical vibration is controversial. It is performed by attaching a mechanical vibrator, usually an eccentric rotating weight, to the weldment. The speed of the drive motor that regulates the frequency of vibration is adjusted until it matches the resonant frequency of the total weldment or of a specific area of the weldment. According to some experts, resonance is not required for stress relieving. Vibration of sufficient power at or near the resonant frequency of the weldment reduces yield point stresses. It is not exactly clear how this happens, but it relates to alternating stresses that may cause slip in individual grains. It is important, however, that a critical cyclic strain amplitude must be exceeded and the weldment must be allowed to deform freely during the treatment. Frequencies up to 100 Hz are used. There is ample proof that this system does relieve stresses, since machining distortion, which is due to the removal of residually stressed surface layers, is reduced by means of this treatment.

The vibratory stress-relieving technique can be used while welding on complex weldments. This technique results in minimum distortion of the weldment during welding and during machining. Mechanical stress relief methods are difficult to control. They have not been accepted by code-making bodies, and there is considerable "black art" involved in accomplishing the desired results.

QUESTIONS

9-1. What five conditions must apply for successful oxyfuel gas cutting?

9-2. What is the best way to compare various makes of cu tting tips?

9-3. What methods are used to guide an automatic flame cutting machine?

9-4. What is stack cutting? What problem is sometimes encountered?

9-5. Explain the oxygen arc cutting process. What metals can be cut?

9-6. Explain the difference between air carbon arc cutting and carbon arc cutting.

9-7. What is the advantage of plasma arc cutting?

9-8. What is the advantage of using water with plasma arc cutting?

9-9. What are the three thermal spraying methods?

9-10. Are powders used for the electric arc spraying process? If so, why?

9-11. Explain how parts are prepared for spraying.

9-12. Can oily metal surfaces be joined with adhesive bonding?

9-13. What are the two major categories of plastics?

9-14. What are the major types of composites?

9-15. Explain how the V-shaped heated area causes bending.

9-16. Show how angle iron can be bent with heat in both directions.

9-17. Is high-carbon steel easily straightened with heat? Why?

9-18. What is interpass temperature?

9-19. Explain the difference between annealing, stress relieving, and normalizing.

9-20. How can you measure the temperature of a heated weldment?

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10

Power Sources for Arc Welding

OUTLINE

10-1 TYPES OF WELDING MACHINES

Special electrical power is required to make a weld with the arc welding processes. The power required is from 10 to 35 V and from 5 to 500 A. Voltages and currents higher and lower than these are sometimes used.

Electric power for arc welding is obtained in two different ways: (1) generated at the point of use or (2) power available from the utility line is converted. There are several methods of electrical power conversion. One is the transformer which converts the relatively high voltages from the utility line to a lower voltage for ac welding. Another is similar and includes the transformer to lower the voltage but is followed by a rectifier which changes alternating current to direct current for dc welding.

There are many ways of describing the electric power used for welding. It can be direct current (dc) or it can be alternating current (ac). Another way is by describing the output characteristics of the power source. It may have constant current (CC), a drooping characteristic, or it may have constant voltage (CV), a flat characteristic. Figure 10-1 shows the principal types of power sources and a classification system. In addition, power sources can be described as rotating machines, static welding machines, electric motor-driven machines,

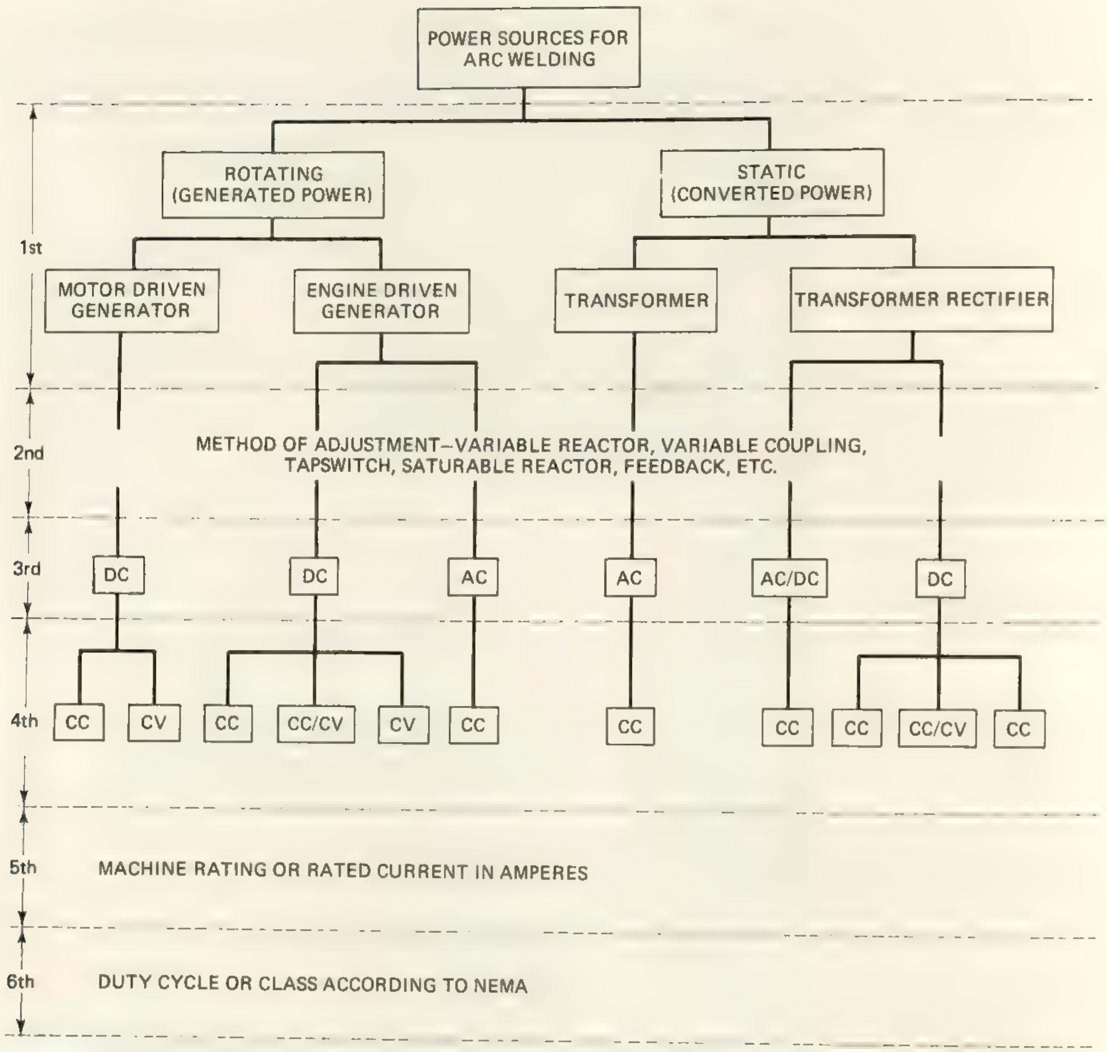


FIGURE 10-1 Simplified system of classifying welding power sources.

engine-driven machines, transformer–rectifiers, utility welding machines, single-operator welding machines, multiple-operator power sources, and so on.

All of the machines, except in the multioperator power sources section, are the single-operator type. These machines are designed to deliver current to only one welding arc.

A second way of classifying welding power sources is by the method of adjustment of the welding power. Controlling the power at the arc is done by changing the strength of magnetic fields. In generators, this is done by switches which reconnect the different coils. In static machines the magnetic fields are changed by varying the induction mechanically, electrically, or by changing the coupling of coils. It can also be done electronically by feedback signals to control circuits.

A third way of classifying welding power sources is by the welding current provided—whether alternating, or direct, or a combination machine that provides both ac and dc.

A fourth way of classifying welding power sources is according to the static volt-ampere characteristic output curve. The conventional or *constant-current* welding machine has the *drooping* volt-ampere characteristic curve. The flat or *constant-voltage* [sometimes called *constant-potential* (CP)] power source has a relatively *flat* volt-ampere characteristic curve. For comparison, the normal output curves and the true constant-current and true constant-voltage curves are shown in Figure 10-2. In both cases the terms are not exact but are accepted and used by the welding industry.

A fifth method of classifying welding power sources is its rating. The rating is the load current obtained from the welding machine without creating excessive temperature rise within the power source. All welding power sources are rated to provide a specific load current at a specific load voltage for a given duty cycle. Ratings in North America are based on the specification of the National Electrical Manufacturers Association (NEMA), "Electric Arc welding Apparatus."[1] Ratings

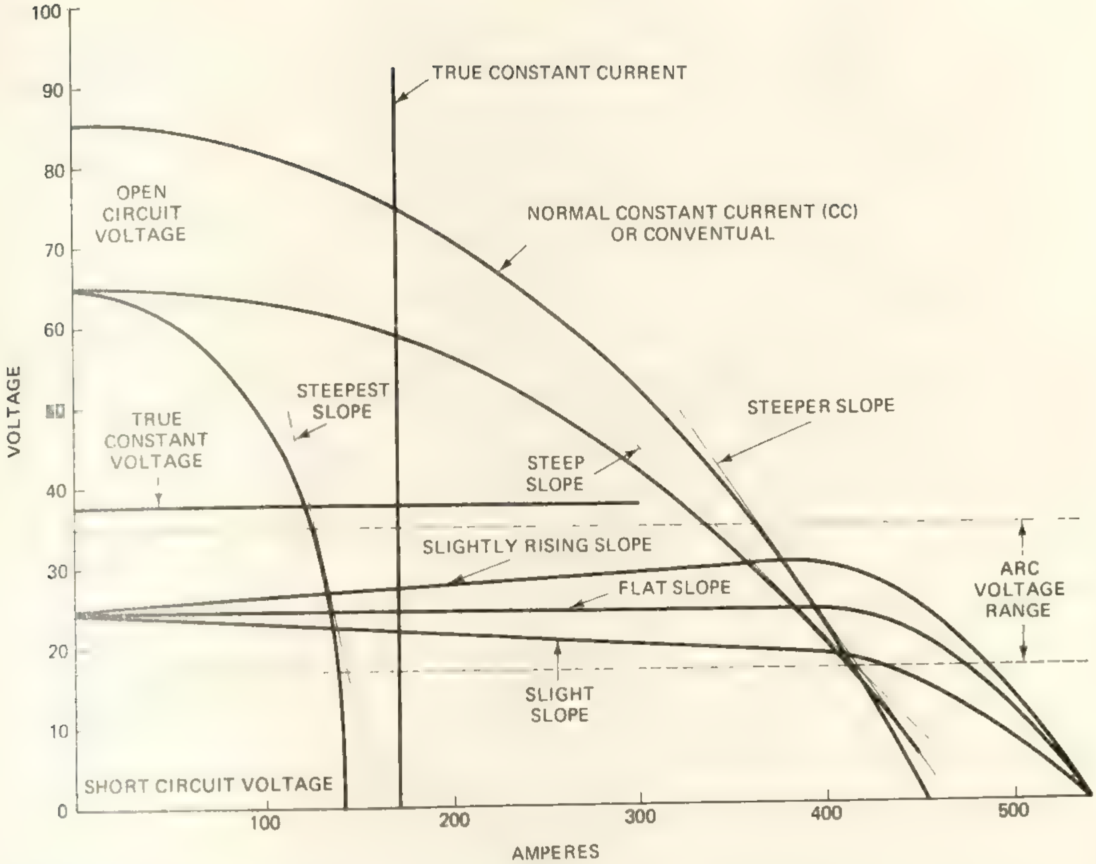


FIGURE 10-2 Static volt-ampere characteristic arcs and slopes.

in some countries are based on the specifications of the International Standards Organization (ISO).[2]

The sixth way of classifying welding power sources is in accordance with the NEMA class. NEMA has established three classes as follows:

- *Class I:* rated output at 60%, 80%, or 100% duty cycle
- *Class II:* rated output at 30%, 40%, or 50% duty cycle
- *Class III:* rated output at 20% duty cycle

Duty cycle is the ratio of arc time to total time in a 10-minute period. The ISO standard and the standard of many European countries use a 5-minute period.

The rating of the welding machine is determined by tests and is related to the static volt-ampere characteristic curve. Machines are rated according to the duty cycle and the specific load voltage. The load voltage standard changes from 28 to 44 V, depending on the size of the machine. Tests are run at the duty cycle specified to determine that specific temperatures are not exceeded within the machine. Refer to NEMA Standard EW-1 for details.[1]

Sometimes a welding machine is required to produce more than its rated output current. This is possible if the duty cycle is reduced. Sometimes it is necessary to use a machine to weld automatically or for 100% of the 10-minute period even though it has a 60% duty cycle. This is possible if the current is reduced below the rating.

Both of these situations can be resolved by use of the following formula:

$$\text{desired duty cycle (\%)} = \frac{(\text{rated current})^2}{(\text{desired current})^2} \times \text{rated duty cycle (\%)}$$

For example, a machine rated at 300 A and 60% duty cycle must be operated at 350 A. What maximum duty cycle can be used?

$$\text{desired duty cycle (\%)} = \frac{(300)^2}{(350)^2} \times 0.60$$

$$= \frac{90{,}000}{122{,}500} \times 0.6 = 44\%$$

Thus to use this machine at 350 amperes the duty cycle

would have to be reduced to 44%. This means welding 4.4 minutes out of every 10 minutes.

In the other situation, the same machine, a 300-ampere 60% duty cycle machine, must be used on an automatic-welding application. It must run for a full 10 minutes, or, at a 100% duty cycle. What output current could be safely obtained from the machine?

$$1.00 = \frac{(300)^2}{(\text{desired current})^2} \times 0.60$$

$$(\text{desired current})^2 = \frac{(300)^2}{1.00} \times 0.60 = 90{,}000 \times 0.6$$

$$\text{desired current} = \sqrt{54{,}00} = 232 \text{ A}$$

Thus for an automatic operation running 10 minutes continuously, the machine output must not exceed 232 A without overloading the power source.

This same determination can be made without using the formula above. Figure 10-3, which is the duty cycle versus ampere curve, is a plot of this formula. The sloping lines show typical machine ratings and by drawing a sloping line parallel to those shown different duty cycles or different load current requirements can be determined.

The terms *slope, variable slope,* and *slope control* tend to be confusing and are often misunderstood with respect to welding machines. The *term* slope relates to the static volt-ampere characteristic curve of the machine. It is defined as the output voltage change to the change in the output current expressed in volts per 100 A. The term applies to both drooping characteristic machines as well as constant-voltage machines. Slope is important within the arc voltage range. Figure 10-2 shows three degrees of slope for both the conventional and the constant-voltage type of power source. In the case of the constant-voltage machine, the three slopes shown are the most widely used. The rising slope is sometimes recommended for GMAW of aluminum but is not too popular. A perfectly flat or true CV curve is normally not used because it has no droop and a small amount of droop improves the stability of the welding arc because it limits the maximum short circuit current.

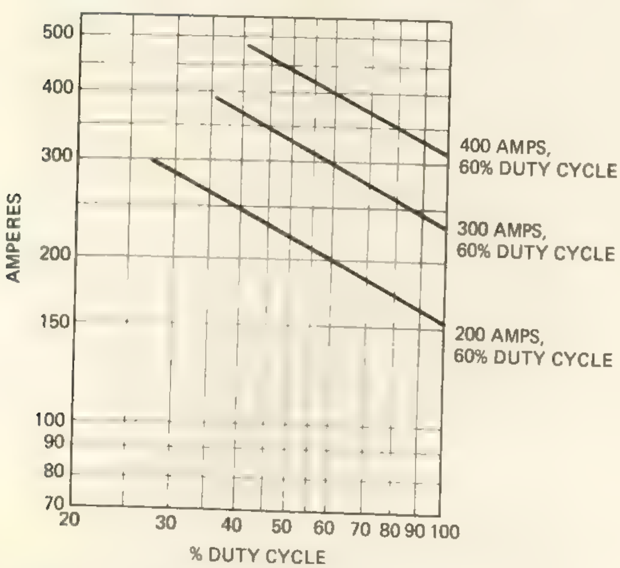
Most constant-voltage machines have a curve close to flat with several curves having additional slope. Slope on the constant-voltage machines is obtained by adding impedance in the output circuit. Most CV machines have three slopes designed for the most widely used welding processes. Adjustments providing for a variable slope or variable inductance are available on some machines. In general, the correct slope is built into the CV machine for the type of welding to be done. As far as the welder is concerned, the slope should be used which provides the best welding arc for the job at hand.

The term *power factor* is an electrical term which is of high interest to the electrical utility company and to plant engineers. In direct current, power is expressed in watts or kilowatts (kW). In a direct-current circuit the product of voltage and amperage entering the circuit is all usable and it all registers on the power meter. With alternating current, however, the kilowatts are used to indicate the usable power while the term kilovolt-ampere (kVA) is used to indicate the total product of amperes times volts delivered by the utility company. The term *power factor* (PF) is the ratio of usable current (kW) to the total current (kVA). When the alternating-current voltage and current are in phase, the power factor is said to be unity or 1. Thus with a unity power factor the kilowatts (kW) equals the kilovolt-ampere (kVA).

The power factor of an industrial company, however, is rarely at unity since most of the electrical loads in the factory consist of motors which are inductive loads that tend to cause the volts and amperes to become out of phase. A single-phase ac transformer welding machine is also an inductive electrical load. This causes the current curve of the alternating cycle to lag the voltage curve by a number of degrees, and this creates what is known as a lagging power factor. Electrical utility companies monitor their industrial customers and establish a power factor for the company. This is then entered into a formula so that the factory will pay a penalty when the power factor is less than unity. The power factor of an industrial plant can be improved or moved toward unity by correction devices, such as power-factor-correcting capacitors or synchronous motors. In the case of single-phase transformer welding machines, power-factor-correcting capacitors can be built into the machine to provide a correction factor bringing the power factor close to unity.

No matter what type of classification is used, the power source must provide "usability" for the welder,

FIGURE 10-3 Duty cycle versus rated current curve.



it must give "welder satisfaction." The power source that will enable the welder to produce good-quality welds using the process specified will be the best machine for the purpose.

10-2 ARC WELDING SYSTEMS

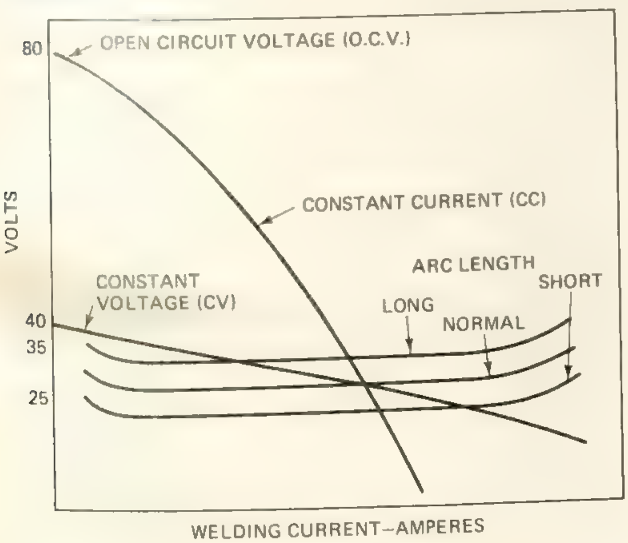
An arc welding system consists of everything needed to make an arc weld. The welding process and method of application largely determine the equipment, filler metals, and the human versus mechanical involvement. Every arc welding system includes a welding power source. For the manual method of application, this, plus the cables, electrode holder, electrode, and work clamp, is the entire system. For semiautomatic or mechanized welding a wire feed system is required, and for automatic welding motion devices are required with complex control systems depending on the level of automation employed. In this section the two basic electrical systems are described. There are two basic types, expressed by the static volt-ampere output characteristics of the power source. The conventional machine is known as the constant-current machine, also known as the variable-voltage type. It has the drooping volt-ampere characteristic curve and has been used for many years for shielded metal arc welding and gas tungsten arc welding.

The other type is the constant-voltage machine. It is sometimes called a constant-potential machine. It has a relatively flat volt-ampere characteristic curve. Both of these terms are slightly misleading since neither machine produces a true constant-current or constant-voltage output; however, these terms are universally used.

The static output characteristic curve produced by both machines is shown in Figure 10-4. The characteristic curve of a welding machine is obtained by measuring and plotting the output voltage and the output current while statically loading the machine. The circuit consists of a pure resistance load which is varied from the minimum or no load to the maximum or short circuit. The constant-current curve shows that the machine produces maximum output voltage with no load, and as the load increases, the output voltage decreases. The no-load or open-circuit voltage is usually about 80 V.

The constant-voltage characteristic curve is essentially flat but with a slight droop. The curve may be adjusted up and down to change the voltage; however, it will never have as high an open-circuit voltage as a constant-current machine. This is one reason that the constant-voltage machine is not used for manual shielded metal arc welding. It is only used for continuous electrode wire welding.

FIGURE 10-4 Characteristic curve for welding power source.

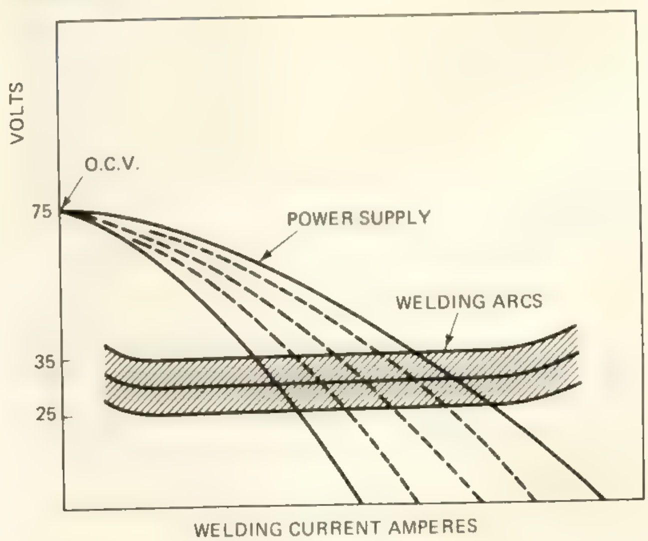


Constant-Current System

The conventional or constant-current power source may have direct-current or alternating-current output. It is used for shielded metal arc welding, carbon arc welding, gas tungsten arc welding, and plasma arc welding. It is used for stud welding and can be used for the continuous wire processes when relatively large electrode wires are used.

There are two types of constant-current welding machines: the single-control and the dual-control machine. The single-control machine has one adjustment, which changes the current output from minimum to maximum. The characteristic volt-ampere curve is shown in Figure 10-5. The shaded area is the normal arc voltage range. By adjusting the current control a large number of output curves can be obtained. The dashed lines show intermediate adjustments of the machine. On tap or plug-

FIGURE 10-5 Curves for single-control welding machine.

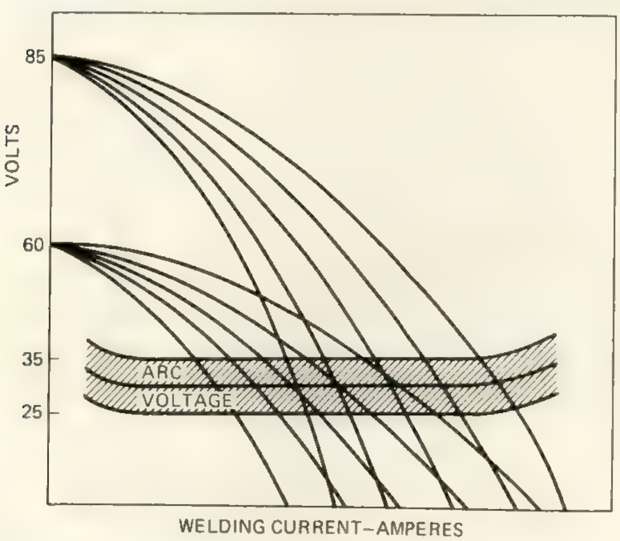


in machines the number of curves will correspond to the number of taps or plug-in combinations available. Most transformer and transformer–rectifier machines are single-control welding machines.

Dual-control machines have both current and voltage controls. They have two adjustments, one for coarse-current control and the other for fine-current control, which also acts as an open-circuit voltage adjustment. The older generator welding machines usually had dual controls. They offer the welder the most flexibility for different welding requirements. These machines have "slope control," which means that the slope of the characteristic curve can be changed from a shallow to a steep slope according to welding requirements. Figure 10-6 shows some of the different curves that can be obtained. Other curves are obtained with intermediate open-circuit voltage settings. The slope is changed by changing the open-circuit voltage with the fine-current control adjustment knob. The coarse adjustment sets the current output of the machine usually in steps from the minimum to the maximum current. The fine-current control will change the open-circuit voltage from approximately 55 V to 85 V. This adjustment does not change arc voltage. Arc voltage is controlled by the welder by changing the length of the welding arc. The open-circuit voltage affects the ability to strike an arc. If the open-circuit voltage is much below 60 V, it is difficult to strike an arc with covered electrodes.

The different slopes possible with a dual-control machine have an important effect on the "feel" and the welding characteristic of the arc. Previously it was pointed out that the arc length can vary depending on the welding technique. A short arc has lower voltage and the long arc has higher voltage. With a short arc (lower voltage), the power source produces more current and with a longer

FIGURE 10-6 Curves for dual-control welding machine.



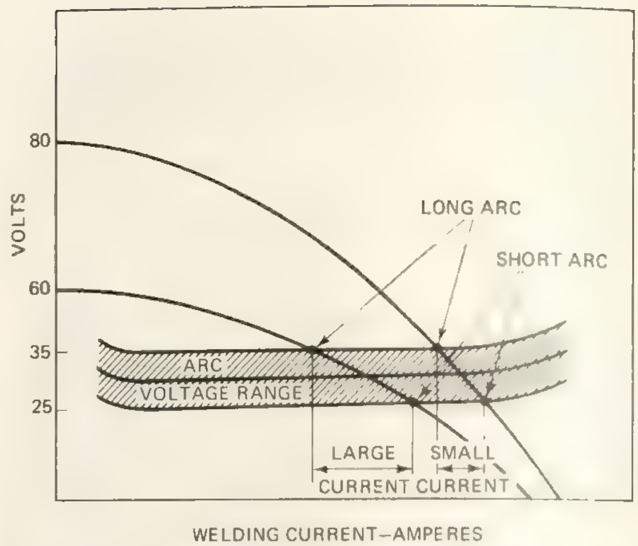


FIGURE 10-7 Volt-ampere slope versus welding operation.

arc (higher voltage), the power source provides less welding current. This is illustrated by Figure 10-7, which shows three curves of arcs and two characteristic curves of a dual-control welding machine. The three arc curves are for a long arc, a normal arc, and the lower curve is for a short arc. The intersection of a curve of an arc and a characteristic curve of a welding machine is known as an *operating point*. The operating point is changing continuously during welding. While welding and without changing the controls on the machine the welder can lengthen or shorten the arc and change the arc voltage from 35 to 25 V. The curves show that with the same machine setting the short arc (lower voltage) is a higher-current arc. Conversely, the long arc (higher voltage) is a lower-current arc. This allows the welder to control the size of the molten pool while welding. When the welder briefly lengthens the arc the current is reduced, the arc spreads out and the molten pool freezes quicker. The amount or volume of molten metal is reduced, which provides the control needed especially for out-of-position work.

The advantage of the dual-control machine is that the welder can adjust the machine for more or less change of current for a given change of arc voltage. Refer again to Figure 10-7 which shows two characteristic curves; both are obtained on a dual-control machine by adjusting the fine-control knob. The top curve shows an 80-V open-circuit voltage and the bottom curve shows a 60-V open-circuit voltage. With either adjustment the voltage and current relationship will stay on the same curve or line. Consider first the 80-V open-circuit curve, which produces the steeper slope. When the arc is long with 35 V and is shortened to 25 V, the current increases. This is done without touching the machine control and is done by the welder by manipulation of the arc. Now consider

the flatter curve, the 60-V open-circuit curve; note that when the arc is shortened from 35 V to 25 V, the welding current will increase almost twice as much as it did when following the 80-V open-circuit curve. The flatter slope curve provides a digging arc where an equal change in arc voltage produces a greater change in arc current. The steeper slope curve has less current change for the same change in arc length and provides a softer arc. There are many characteristic curves between the 80- and 60-V open-circuit voltage curves, and each allows a different current change for the same arc voltage change. This ability to control the current in the arc over a fairly wide range is extremely useful for making pipe welds. Many experienced welders prefer the dual-control machine for all position welding because of this slope control.

The rectifier welding machine, technically known as the transformer–rectifier, produces direct current for welding. These machines are essentially single-control machines and have a static volt-ampere output characteristic curve similar to that shown by Figure 10-5. These machines, even though not as flexible as the dual-control motor generator, can be used for all types of shielded metal arc welding where dc is required. The slope of the volt-ampere curve through the welding range is generally midway between the maximum and minimum of a dual control machine.

The static volt-ampere characteristic curve of an ac power source will be the same as that shown by Figure 10-5. Some transformer welding power sources have fine and coarse adjustment knobs, but these are not dual-control machines unless the open-circuit voltage is changed appreciably. The difference between ac and dc welding is that the voltage and current pass through zero 100 or 120 times per second according to line frequency or at each current reversal. Reactance designed into the machine causes a phase shift between the voltage and current so that they both do not go through zero at the same instant. When the current goes through zero the arc is extinguished, but because of the phase difference there is voltage present which helps to reestablish the arc quickly. The degree of ionization in the arc stream affects the voltage required to reestablish the arc and the overall stability of the arc. Arc stabilizers (ionizers) are included in the coatings of electrodes designed for ac welding, to provide a stable arc.

The constant-current welding machine can be used for some automatic welding processes. The wire feeder and control must duplicate the motions of the welder to start and maintain an arc. This requires a complex system with feedback from the arc voltage to compensate for changes in arc length. The constant-current power supplies are rarely used for very small electrode wire welding processes.

Arc welding machines are now available with true constant-current volt-ampere static characteristics, within the arc voltage range as shown in Figure 10-8. A welder using this type of machine has little or no control over welding current by shortening or lengthening the arc, since the welding current remains the same whether the arc is short or long. This is a great advantage for gas tungsten arc welding since the working arc length of the tungsten arc is limited. In shielded metal arc welding to obtain weld pool control, it is necessary to be able to change the current level while welding. This is done by the machine, which can be programmed to change from a high current (HC) to a low current (LC) on a repetitive basis, known as pulsed welding. In pulsed current welding there are two current levels, the high current and low current, sometimes called background current. By programming a control circuit, the output of the machine continuously switches from the high to the low current as shown by Figure 10-9. The level of both high and low current is adjustable. In addition, the length of time for the high and low current pulses is adjustable. This gives the welder the necessary control over the arc and molten weld pool. Pulsed current welding is useful for shielded metal arc welding pipe when using certain types of electrodes. Pulsed arc is very useful when welding with the gas metal arc welding process. Pulse rates can vary from a few per second up to hundreds of pulses per second.

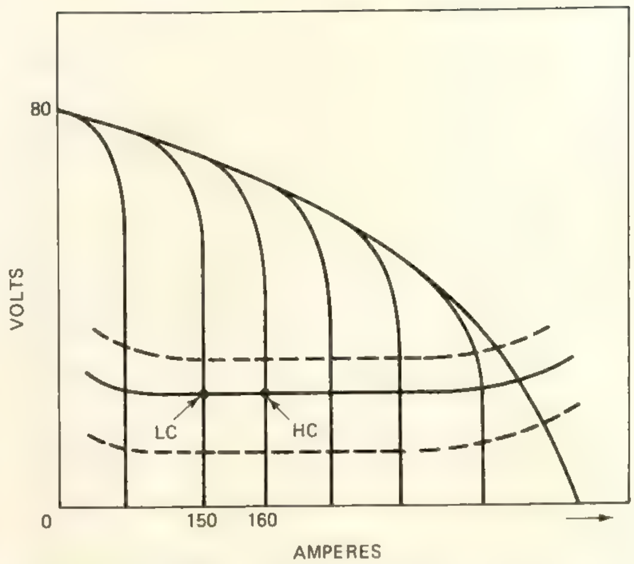


FIGURE 10-8 Volt-ampere curve for true constant-current machine.

Constant-Voltage System

The constant-voltage welding machine and the CV system of automatic arc length control is very popular. The CV principle of operation was introduced at about the same time as gas metal arc welding. It was the combination of these two developments that has made gas metal arc welding extremely popular. Prior to the introduction of

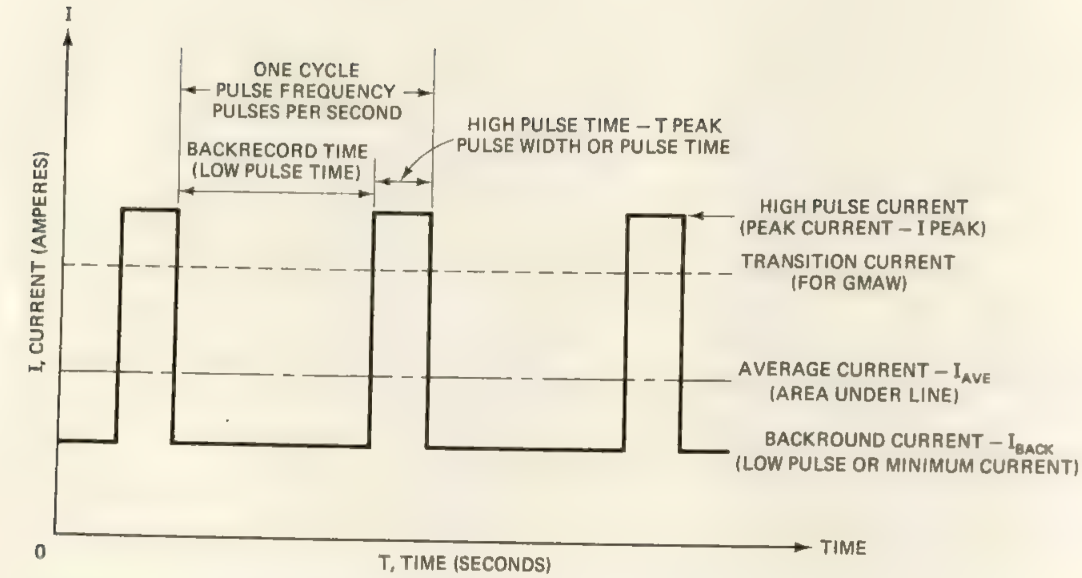


FIGURE 10-9 Pulsed-current welding.

the constant-voltage welding machine, the drooping characteristic type of power source was employed with the voltage-sensing electrode wire feed systems. The reaction time of these systems was not sufficiently fast to avoid burnback and stubbing when using fine wire gas metal arc apparatus. Despite its widespread use, the CV principle of welding needs a thorough explanation.

The CV electrical system is not new to the electric power industry. It is the basis of operation of the entire commercial electric power system. The electric power delivered to your house and available at every receptacle has a constant voltage (Figure 10-10).

This voltage is maintained at each outlet, whether a small light bulb with a very low wattage rating or a heavy-duty electric heater with a high wattage rating is connected. The current that flows through each of these circuits will be different based on the resistance of the particular item or appliance in accordance with Ohm's law. For example, the small light bulb will draw less than 0.01 A of current, while the electric heater may draw over 10 A. The voltage throughout the system remains constant, but the current flowing through each appliance depends on its resistance or electrical load. The same principle is utilized by the CV welding system.

This relationship is the basis of the simplified control for wire feeding using constant voltage. Instead of regulating the electrode wire feed rate to maintain the constant arc length, as is done when using a constant current power source, the electrode wire is fed into the arc at a fixed speed and the power source is designed to provide the necessary current to melt off the electrode wire at this same rate. This concept prompted the development of the constant-voltage welding power source.

The volt-ampere characteristics of the constant voltage power source shown in Figure 10-11 was designed to produce substantially the same voltage at no load and

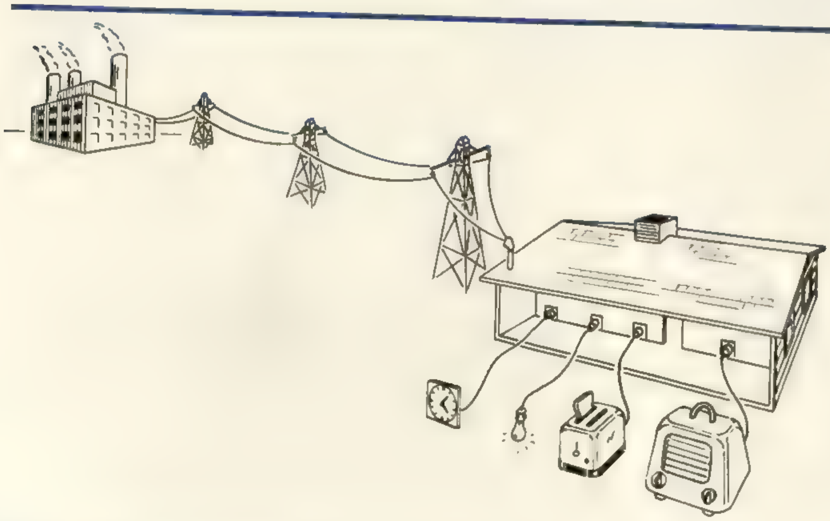


FIGURE 10-10 Constant-voltage system.

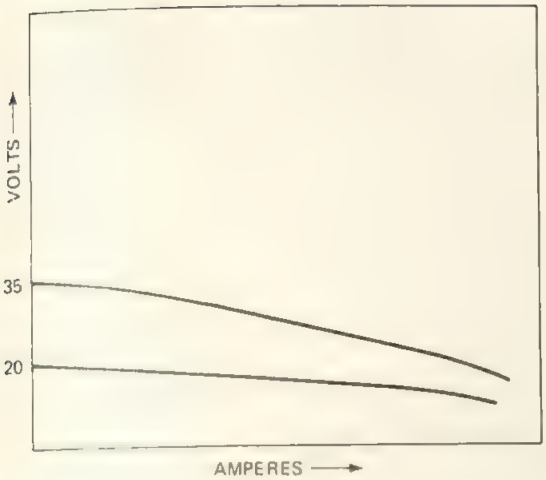


FIGURE 10-11 Static volt-ampere characteristic curve of CV machine.

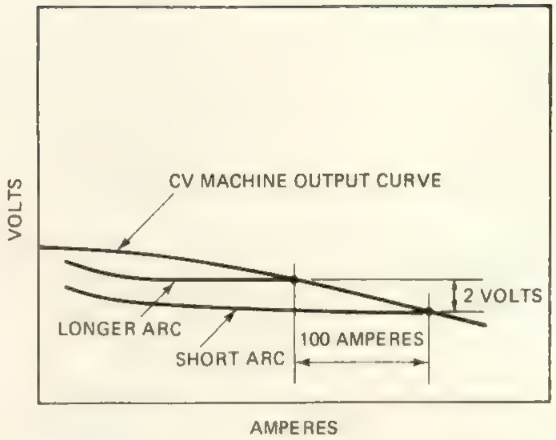


FIGURE 10-12 Static volt-ampere curve with arc range.

at rated or full load. If the load in the circuit changes, the power source automatically adjusts its current output to satisfy this requirement and maintains essentially the same voltage across the output terminals. This system assured a self-regulating arc based on a fixed rate of wire feed and a constant voltage power source. The simplified controls did not require complex circuitry and reversal of the wire feed drive motor.

Another way to understand the constant voltage system is to consider the factors that make up the electrical resistance load in the external portion of the welding circuit. These resistances or voltage drops occur in the welding arc and in the welding cables and connectors, in the welding gun, and in the electrode length beyond the current pickup tip. These voltage drops add up to the output voltage of the welding machine and represent the electrical resistance load on the welding power source. When the resistance of any component in the external circuit changes the voltage balance will be achieved by changing the welding current in the system. The greatest voltage drop occurs across the welding arc. The other voltage drops in the welding cables and connections, and so on, are relatively small and constant. The voltage drop across the welding arc is directly dependent upon the arc length. A small change in arc volts results in a relatively large change in welding current. Figure 10-12 shows that if the arc length shortens slightly or 2 V, the welding current increases by approximately 100 A. This change in arc length greatly increases the melt-off rate and quickly brings the arc length back to normal.

The constant-voltage power source is continually changing its current output in order to maintain the voltage drop in the external portion of the welding circuit. Changes in wire feed speed which might occur when the welder moves the gun toward or away from the work are compensated for by momentarily changing the current and the melt-off rate until equilibrium is reestablished. The same corrective action occurs if the wire feeder has a temporary reduction in speed. The CV power source and fixed wire feed speed system is self-regulating. It is an excellent wire feed system, especially for semiautomatic welding, since movement of the cable assembly often changes the drag or feed rate of the electrode wire. The CV welding power source provides the proper current so that the melt-off rate is equal to the wire feed rate. The arc length is controlled by setting the voltage on the power source. The welding current is controlled by adjusting the wire feed speed.

The characteristics of the welding power source must be designed to provide a stable arc when welding with different electrode sizes and metals and in different atmospheres. Most constant-voltage power sources have taps or a means of adjusting the slope of the volt-ampere curve. Experience indicates that a curve having a slope of 1½ to 2 V per hundred amperes is best for gas metal arc welding with nonferrous electrodes in inert gas, for submerged arc welding, and for flux-cored arc welding with larger-diameter electrode wires. A curve having a medium slope of 2 to 3 V per 100 A is preferred for welding with CO_2 gas-shielded metal arc welding and for smaller flux-cored electrode wires. A steeper slope of 3 to 4 V per 100 A is recommended for short-circuiting arc transfer. These three slopes are shown in Figure 10-13. The flatter the curve, the more the current changes for an equal change in arc voltage.

The dynamic characteristics of the power source must be carefully engineered. Refer again to Figure 10-12. If the voltage changes abruptly with a short circuit, the current will tend to increase quickly to a very high value. This is an advantage in starting the arc but will create unwanted spatter if not controlled. It is controlled by adding reactance or inductance in the circuit. This changes the time factor or response time and provides for a stable arc. In most machines a different amount of inductance is included in the circuit for the different slopes.

The constant-voltage welding power system has its

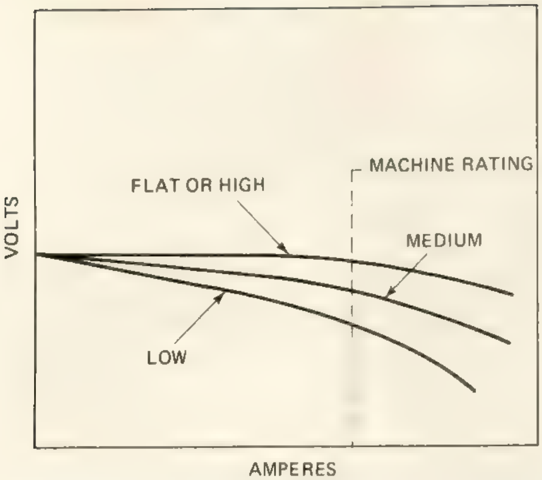


FIGURE 10-13 Various slopes of characteristic curves.

greatest advantage when the current density of the electrode is high.

Direct-current electrode positive (DCEP) is used for gas metal arc welding. When dc electrode negative (DCEN) is used, the arc is erratic and produces an inferior weld. Direct-current electrode negative (DCEN) can be used for submerged arc welding and flux-cored arc welding.

The constant-voltage principle of welding with alternating current is normally not used. It can be used for submerged arc welding and for electroslag welding, but is not popular.

The constant-voltage power system should not be used for shielded metal arc welding. It may overload and damage the power source by drawing too much current too long. It can be used for carbon arc cutting and gouging with small electrodes. Figure 10-14 shows the different arc welding processes and the type of welding machines that can be used.

There are two factors that determine the arc stability. The first is the static volt-ampere characteristic curve. The second is the dynamic characteristics of the machine. This relates the two extreme conditions; the short-circuit voltage and the open-circuit voltage. The change of the voltage and current provides the dynamic characteristics. At the short circuit the voltage drops to approximately zero. When the short circuit clears, the voltage will rise quickly followed by a stabilization of the voltage to a value below the open-circuit voltage, called the *recovery voltage*. The current rises rapidly during the short-circuit period. When the short is removed, the current quickly stabilizes to the normal value. Arc stability is related to the ability of the power source to reignite the arc smoothly following the short circuit. The quick-rising voltage must exceed the arc voltage if arc reigniton is to occur. Excessive overshoot of welding current cannot be tolerated. An excessively fast increase in current during the period of initial shorting results in what is called *overshoot* and causes excessive weld metal spatter. Additionally, an excessively fast decrease in the current results in instability which might extinguish the newly formed arc. Current recovery should occur within one or two electrical cycles. The dynamic characteristic of the machine is sometimes called the "response time," which is the time required to return to steady or average conditions (Figure 10-15). The welding machine must contain the proper balance of impedance or inductance to stabilize the output of the machine quickly.

	Welding Machine Output Characteristics Utilizing:		
	Direct (DC)		Alternating (AC)
Arc Welding Process	CC Drooping	CV Flat	CC Drooping
Nonconsumable electrode process			
Gas tungsten arc welding (GTAW)	Yes	No	Yes
Plasma arc welding (PAW)	Yes	No	No
Carbon arc welding (CAW)	Yes	No	2 carbons
Stud welding (SW)	Yes	Possible	No
Consumable electrode processes			
Shielded metal arc welding (SMAW)	Yes	No	Yes
Gas metal arc welding (GMAW)	—	—	—
Inert gas—nonferrous MIG	Possible	Yes	No
Spray arc transfer	Possible	Yes	No
Globular transfer	Possible	Yes	No
Short-circuiting transfer	No	Yes	No
Pulsed arc transfer	Special	Special	Possible
Flux-cored arc welding (FCAW)	Yes	Yes	Expmtl
Submerged arc welding (SAW)	Yes	Yes	Yes
Electrogas welding (EGW)	Possible	Yes	No
Electroslag welding (EW)	Possible	Yes	Yes

FIGURE 10-14 Arc welding process versus welding power source type.

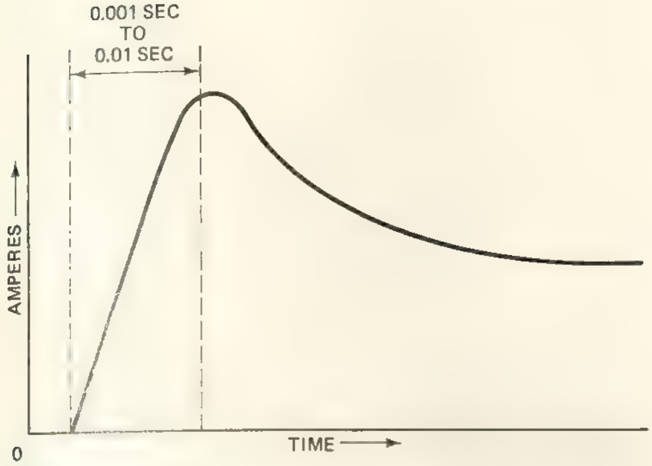


FIGURE 10-15 **Dynamic characteristic versus response time.**

10-3 ROTATING WELDING MACHINES

The generator is the oldest, the most reliable, and the most versatile welding power source. The generator can produce a rising-slope, slightly drooping, or steeply drooping type of output curve. It can be used for all of the arc welding processes.

The rotating generator can be driven by an air motor, an electric motor, normally an induction type, or by an internal combustion engine fueled by gasoline, diesel oil, liquid petroleum gases, or natural gas. The engine can be air cooled or water cooled. The generator can be driven by a power takeoff, or by belts and pulleys from a source of rotating power.

The most popular use of the engine powered generator is for manual shielded metal arc welding. It is widely used by the construction industry and for cross-country pipe welding. Electrical generation is based on the principle that "when a conductor moves in a magnetic field so as to cut lines of force an electromotive force (EMF) is generated." An actual generator is much more complex since there are multiple poles and hundreds of loops that cut the magnetic fields.

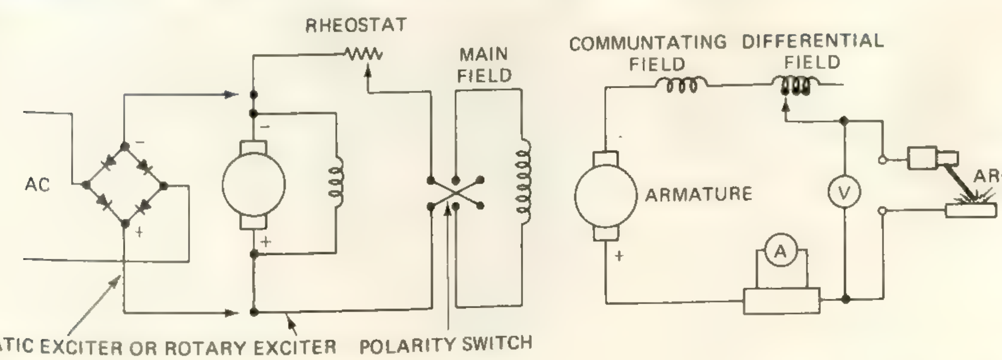
A generator consists of a stationary frame or stator and a rotating armature. The frame contains an extremely efficient magnetic circuit consisting of multiple magnetic poles. Each field pole is surrounded by coils of many turns arranged so that two of the poles are north and two of the poles are south. These coils are known as the main field windings, and power to energize them is supplied from an exciter. The output voltage of the welding generator is controlled by a variable resistance or rheostat in the main field circuit. More or less excitation voltage causes an increase or decrease of magnetic lines in the electromagnetic circuit and raises or lowers the open-circuit voltage of the welding machine.

Additional magnetic poles known as interpoles are included in the frame of many welding machines. There are usually four interpoles in welding generators. Two of these are called shunt poles and have windings known as shunt field coils. The main welding current flows through the windings of these coils, which are known as series bucking fields or differential series fields. More or less of the main welding current is fed through these coils by means of the diverter or range switches. This serves to reduce the output by setting up magnetic fields in opposition to the main field as welding current is increased. This produces the drooping volt-ampere characteristic necessary for constant current welding. By means of range switches more or fewer turns of the differential coils are connected to the output terminals and this determines the amount of current produced by the machine. The other two coils, called the commutating poles, are surrounded by windings known as the commutating field. The commutating poles are the same polarity as the main field poles and provide for sparkless commutation of the generator. Figure 10-16 is a circuit drawing of a separately excited differentially compound welding generator circuit.

On constant-voltage welding generators the differential series field is not reversed or bucking but is additive, and this makes the machine produce a constant voltage output.

When generators are driven by engines they will include an exciter generator. This is a small shunt-connected generator mounted on the same shaft as the main gener-

FIGURE 10-16 **Circuit diagram of generator welding machine.**



ator. This exciter is used to provide current for the field coils of the main generator. It is also used to provide auxiliary power for electric tools, lights, wire feeders, etc. Either alternating or direct current can be obtained from the exciter generator. Some engine-driven machines are called *self-excited* and utilize residual magnetism to provide field coil current. Self-excitation is used only for smaller machines.

For motor-driven generators the exciter generator may be replaced by a solid-state rectifier bridge circuit to provide the dc current necessary for the field coils. In either case the amount of current provided to the field coils determines the open-circuit output voltage of the generator.

The rotating part of the welding generator is called a drum armature. This is mounted on the shaft and consists of many windings which are loops around an iron core that rotates within the magnetic field produced by the poles of the generator. The ends of these winding loops can be connected to slip rings or to a commutator bar. The output of a coil rotating within a magnetic field is an alternating current. When the opposite ends of the winding loop are each connected to a separate slip ring the output of the commutator will be alternating current. This is the normal way that large power generators are constructed. The commutator, which is made of many bars or segments, has the separate ends of the winding loop connected to segments on the opposite side of the circumference of the commutator. By means of carbon brushes on opposite sides of the commutator the current is reversed each quarter revolution. Thus the commutator is a mechanical rectifier since the opposite bars are connected to brushes only when that particular loop winding is generating the maximum EMF as it passes through the magnetic field. An instant later the brushes are connected to a different loop, and so on. By means of progressive connections of the winding loops to the segments, direct current is obtained at the brushes in contact with the commutator. The commutator and armature can be seen in Figure 10-17, a cutaway view of a generator welding machine. The construction of the armature can better be seen in Figure 10-18. The large commutator is for welding current and the small commutator is for the exciter generator. Notice the sirocco-type fan for pulling air through the generator to provide cooling.

The carbon brushes in contact with the commutator take the generated current through the various coils and to the terminals of the machine. In older machines stabilizing coils or an inductor was placed in series with the output current. In newer machines, sufficient inductance is built into the generator so that external stabilizing coils are not required.

For some welding generators it is possible to reverse the polarity of output. The terminals on a generator are normally marked positive and negative or electrode and work. By utilizing a reversing switch between the output

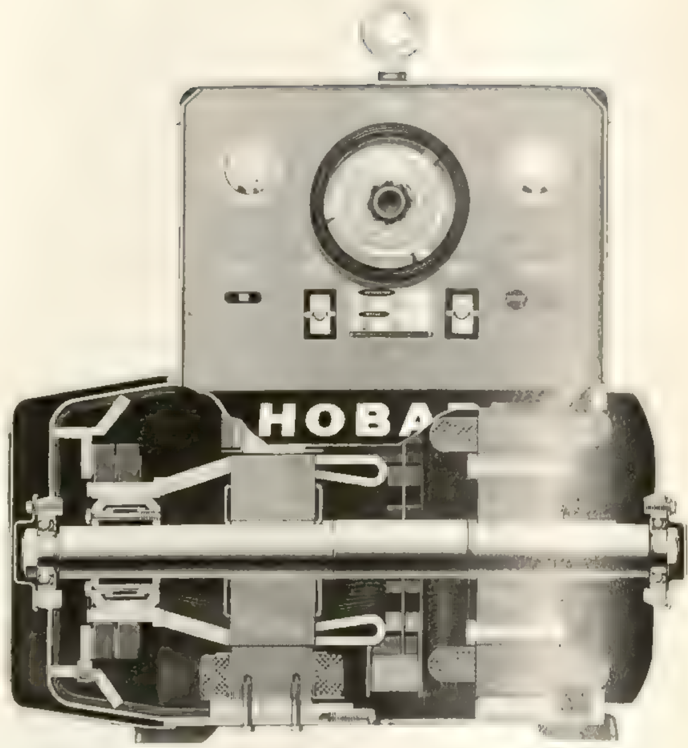
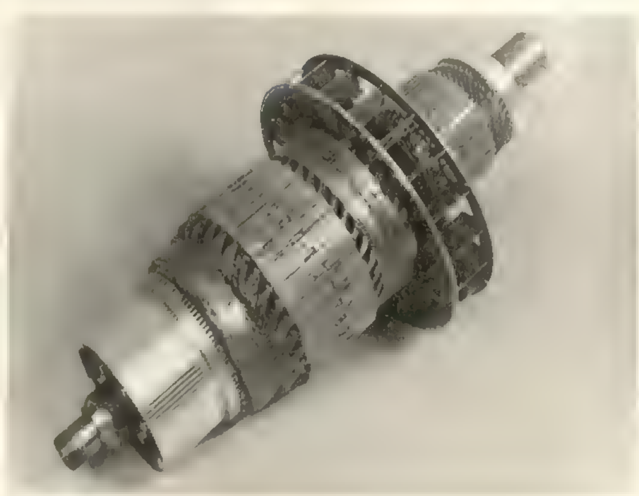


FIGURE 10-17 Cutaway view of motor generator

of the exciter, the field coils change their magnetic polarity. When the polarity of the field coils is changed the polarity of the output of the generator is also changed.

The speed of rotation of a generator welding machine with four poles is 1800 rpm. This produces 60-Hz power from the exciter generator, which can be used to run power tools, and so on. To produce 50 Hz power the generator would be operated at 1500 rpm. Two pole generators operate at 3600 rpm for 60 Hz or 3000 rpm

FIGURE 10-18 Armature of generator welding machines.



for 50 Hz. Engine-driven equipment will run at a slightly higher speed without load, but when under load should approximate 1800 rpm. Some water-cooled engine machines have idling devices that reduce the rotating speed and conserve fuel when not welding. When the generator is operated by an electric motor, the motor is normally a squirrel-cage type of induction motor designed to run at the above-mentioned speeds. These motors are powered by three-phase current, which provides balanced load conditions to the utility line.

The induction motors produce a lagging power factor. The exact amount or degree of lagging power varies with the load. The amount of power factor in percentage is given by the performance curve of a single operator motor generator welding machine. In some factories, this may be significant and may require the use of power factor corrective devices. These are normally capacitors placed across the input of the electric induction motor.

The direction of rotation of the motor must be correct for the generator. Most generators have an arrow showing the direction of rotation. The three-phase line connected to the motor must have two leads reversed if the rotation is opposite the direction of the arrow. In North America, welding machines are normally powered by 230 V or 460 V, 60 Hz. The power input cable should be sized in accordance with current input. This applies also to fuses, switchboxes, and so on.

Usually the driving motor is equipped with a starting device which connects the motor to the power line without causing excessive current surge when the motor starts. The starter also contains a thermal overload, which would disconnect the motor in the event of overheating. Special starting switches known as star-delta switches can also be used and are sometimes required by power companies. In this way, the welding machine is started without load at a slower speed for a brief instant and then switched over as speed builds up.

Some engine-driven welding machines will produce only alternating current. Slip rings are used instead of the commutator. Brushes ride against the slip rings taking off the alternating current produced by the revolving loop windings as they pass through the magnetic field. They are normally powered by air-cooled engines.

The third type of generator is known as the rotating field or alternator type. In this case, the armature is replaced by a rotor, which has four magnetic field coils on an iron core. The frame of the machine, or the *stator*, holds the armature coils in slots. The generation of the EMF is the same since the loop windings cut through the magnetic field. In this case, however, the magnetic field is rotating and the loops are stationary. It is necessary to provide current for the field coils which are rotating. This is done in different ways. In one case, an exciter generator is placed on the same shaft with the rotating fields and its output is taken off as direct current by brushes on the exciter commutator. In some cases, the exciter is an alternator and the output is rectified by diodes. This output is sometimes used for auxiliary power. More importantly, however, this output goes through a control rheostat to adjust the amount of current to the fields and thus adjust the output of the machine. The field current is fed back into the rotating fields by means of slip rings. The output of the alternator is then produced in the armature coils in the stator. This is alternating current, which is then rectified by power diodes for direct current welding.

There is another variation, known as the *brushless generator*. In this machine a small portion of the welding current is controlled and used to excite the field windings of the exciter generator's fixed stator. Ac power is then generated in the rotating armature of the exciter, which is fed to a solid-state diode rectifier bridge mounted on the rotating shaft. The diodes produce direct current which is used to provide field current for the rotating fields of the main generator, also revolving on the main shaft. The rotating field produces the magnetic lines of force, which generate alternating current in the armature windings of the stator of the main generator. This alternating current is then rectified by power solid-state diodes and is the direct-current output for welding. This dc welding brushless generator can be powered by engines.

10-4 TRANSFORMER WELDING MACHINES

Transformers have been used as a welding power source since about 1920. They are considered static electrical machines since rotating motion (except fans) is not used. Holslag is credited with inventing the transformer-type welding power source.[3]

Holslag discussed the square-wave output, which helped stabilize the welding arc by making the current flow through zero quicker. He also covered the phase-shifting aspects to help stabilize the arc. It was not until the covered electrode became widely used that the transformer power source became popular.

The principle of operation of a transformer is shown in Figure 10-19. It employs mutual induction between two coils in a magnetic circuit. The primary coil causes magnetic lines of force to build up to the maximum in one direction, during one half-cycle of flow, and then collapse. The magnetic lines then build up in the opposite direction to a maximum during the other half-cycle of current flow and then collapses. The secondary coil is in the same magnetic field and the magnetic lines of force will cut across the second coil and induce an EMF in it. A welding transformer is a "step-down" transformer and the voltage relationship between the primary and secondary is determined by the number of turns or loops in each coil. This is shown by the formula $N_p/N_s = V_p/V_s$ - (open circuit). The primary coil has a

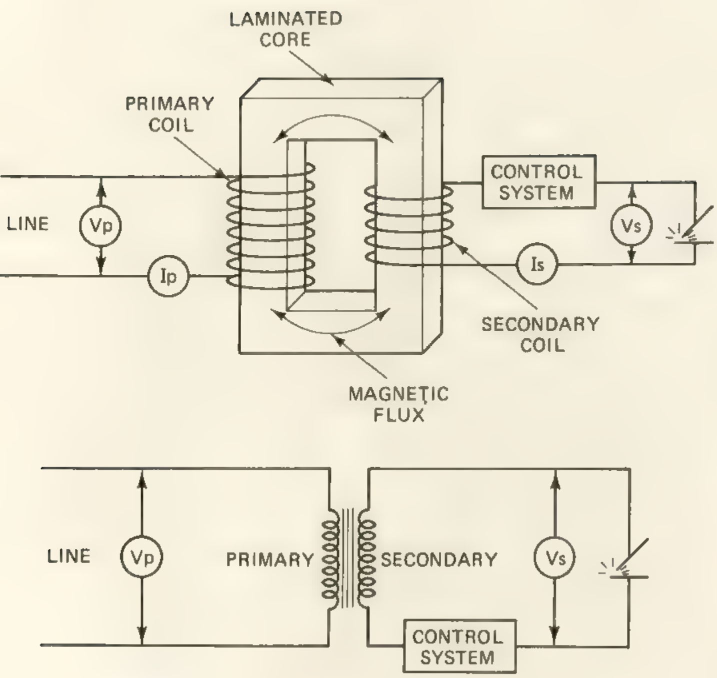


FIGURE 10-19 Transformer principle for alternating current.

large number of turns and accommodates a higher voltage. The secondary coil has fewer turns and a lower voltage (open circuit). The power or watts in both the primary and secondary coils are approximately the same except for the electrical losses. The product of the primary voltage times primary current equals the product of the secondary voltage times secondary current while welding as shown by the formula $V_p \times I_p = V_s \times I_s$ - (while welding).

Changing the magnetic coupling of the two coils changes the current output of the welding transformer. The magnetic coupling can be increased by moving the coils closer together or by increasing the strength of the magnetic field coupling them (Figure 10-20). The wave shape of the secondary output is essentially the same as the primary, normally sinusoidal. In addition, the transformer isolates the incoming primary power from the output of the welding machine. The transformer principle is utilized in most static-type welding power sources.

Varying the output of a transformer welding machine can be accomplished by a mechanical or electrical method. The most common mechanical methods are described below.

1. Placing a resistor in series with the output and switching to different-sized resistors to vary the output
2. Tapping the secondary coil of the transformer with switches or plugs
3. Tapping a reactor or placing a variable reactor in the secondary circuit
4. Moving the primary or secondary coil with respect to the other coil
5. Moving an iron core in a reactor or in the secondary circuit
6. Placing a moving iron shunt between the primary and secondary coils

Methods 1 to 3 and 5 adjust the amount of impedance in the transformer secondary circuit. Methods 4 and 6 adjust the magnetic flux coupling between the primary and secondary of the transformer. There are advantages and disadvantages to each of these systems.

Method 1 has the disadvantage of heat wasted in the resistance in series with arc. It is rarely used today.

Method 3 uses a tapped reactor in the secondary to change impedance. It does not provide for continuous adjustment of output current. The number of taps restricts the current selection available. This system is relatively efficient and is used for small limited-input-type welding transformers.

Method 4 changes the reactance of the transformer by changing the position of the primary and secondary coils with respect to each other. Moving a coil away from the other permits a greater amount of leakage flux to flow between them and increases the reactance of the transformer. This reduces the current output. The coils are moved toward or away from each other by means of a lead screw which provides continuous adjustment. In time the moving coil may loosen and vibrate and cause noise. The connectors attached to the moving coil will be continually flexed in operation, which can create service problems.

Method 5 uses a moving iron core in the reactor in the secondary circuit. Moving the core causes a change in the air gap which changes the reactance. The larger the air gap, the smaller the impedance value and the higher the output current. As the air gap is reduced, impedance increases and the welding current is reduced.

Method 6 uses the moving core in a different way to adjust the reactance of the transformer. In this method an iron core called a "shunt core" is moved between the primary and secondary coils. This movement varies the leakage flux between the primary and secondary and adjusts the output current.

Movable parts tend to vibrate, wear, and become loose, which creates undesirable noise. Mechanically moving parts such as lead screws wear and become dirty and difficult to move. On large machines adjustments that involve movement can be motorized for remote current control.

These brief descriptions are simplified explanations of the transformer welding power source designs. A cer-

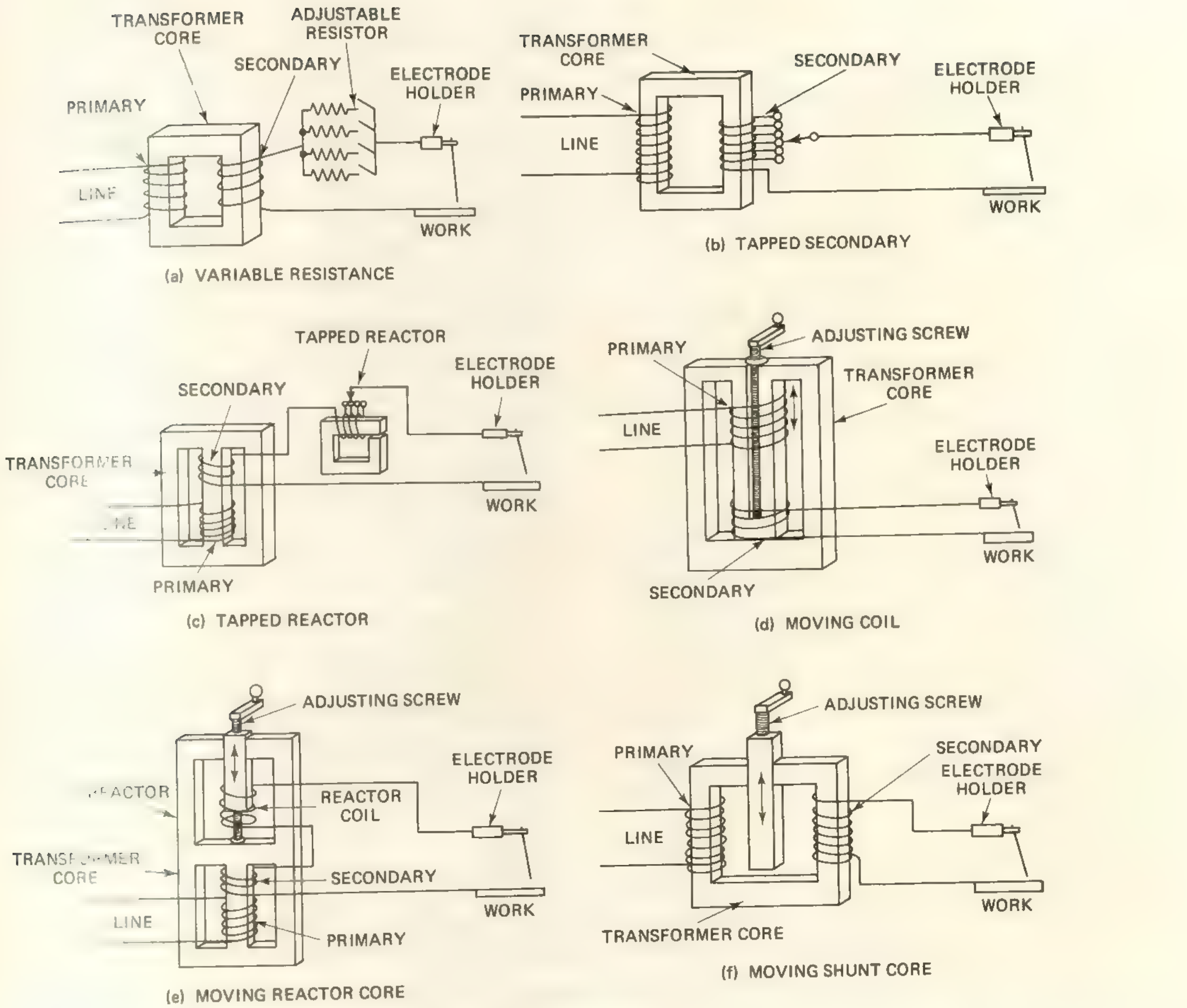


FIGURE 10-20 Mechanical methods of controlling transfer output.

tain amount of impedance or droop must be built in the power source to make it usable. Without the secondary impedance the transformer welding machine would have constant-voltage characteristics. A constant-voltage or flat characteristic alternating-current power source is rarely used for arc welding.

The alternating-current power source, even with proper output characteristics, must rely on ionizing elements in the arc atmosphere in order to maintain a stable arc. Since the alternating current continuously varies from positive to negative, the arc goes out each half-cycle as the voltage passes through the zero point. The ionizing elements added to the flux coating of an electrode help arc reignition each half-cycle, which stabilizes the arc. It is very difficult to use bare electrodes or bare solid electrode wire with alternating current, without some sort of arc ionizer or stabilizing elements in the arc atmosphere. In the case of gas tungsten arc welding, high-frequency current is sometimes employed to ionize the arc gap.

An electrical method of controlling the transformer output eliminates the moving parts with their possible service problems (Figure 10-21). It is the beginning of the total electrical control systems, which are also used on transformer rectifier welding machines. It is made possible by the use of a diode bridge rectifier. In this system the reactor in the secondary circuit is used to regulate the output current. Direct current from the diode bridge is introduced into the reactor, which tends to saturate its magnetic field. When there is no dc current flowing in the reactor coil, it has its maximum impedance and thus

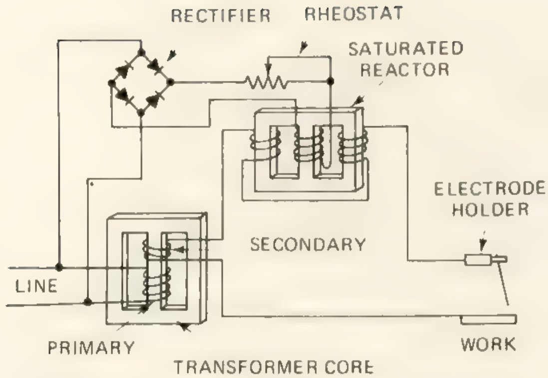


FIGURE 10-21 **Electrical method of controlling transformer output.**

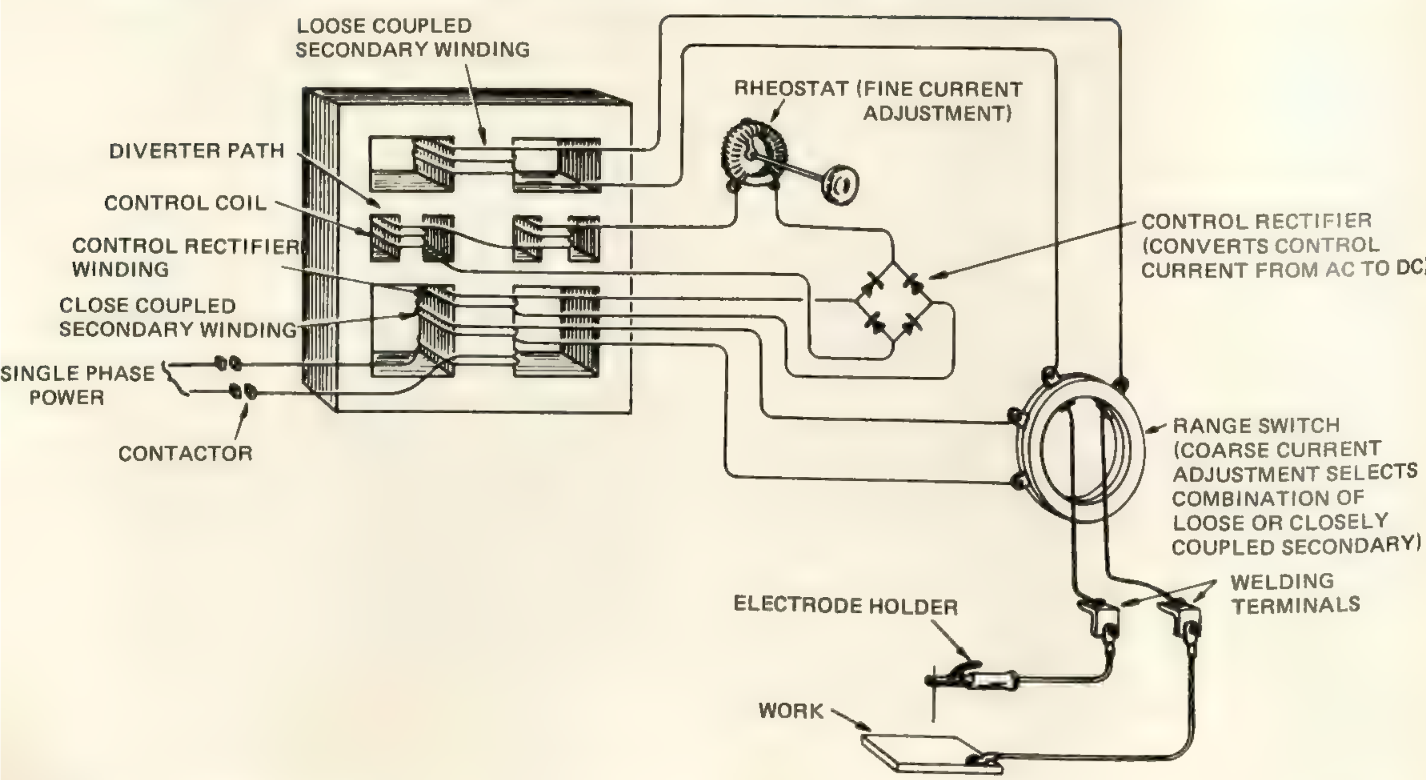
minimum output of the transformer welding machine. As the dc current is increased, by means of the rheostat in the direct-current circuit, the magnetic field contains more direct current or more continuous magnetic lines of force in the magnetic circuit. Impedance of the reactor is decreased and the output current of the welding transformer is increased. This electrical method of control is widely used in industrial welding machines. A simplified version of this design is shown in Figure 10-22.

Single-operator constant-current welding transformer power sources are available in all three NEMA classes. They are available with current outputs ranging from 50 to 1000 A. One of the most popular ac transformer welding machines is the NEMA class III type, known as "utility" or "farm welders" and commonly called "limited-input welding machines." These were originally designed to have a limited input current at their rated output so that they could be used in rural areas on available utility power lines. They are rated with a 20% duty cycle and are used for light-duty repair work and hobbies. They are also covered by Underwriters' Laboratories.[4]

The NEMA class II welding transformers are not too popular. The NEMA class I welding machines are industrial-type welding power sources rated at 60%, 80%, or 100% duty cycle. The 60% duty cycle machines are used for manual shielded metal arc welding in industrial applications. The 100% duty cycle machines are used for automatic submerged arc welding.

Transformer welding machines are normally air cooled. The small, light-duty or limited-input machines use convection cooling and rely on air that normally circulates through the louvers in the case of the machine. Heavy-duty and industrial-type transformer power sources have fans to cool the machine. Air is circulated through the case by means of a fan. Overheating may occur if the fan is not operating or if air passages are blocked. Oil-cooled transformer power sources that utilize circulating oil in a sealed circuit are available for

FIGURE 10-22 **Modern transformer welding power source.**



special installations where dusty and corrosive environments are encountered. Circulating water from an external source is sometimes used for cooling welding power sources. This type of machine is used primarily in automobile manufacturing plants.

The transformer welding machine is the most efficient of any welding machine from the electric power point of view. It has the highest efficiency, the lowest no-load losses, and with proper power factor correction, a good power factor. Figure 10-23 shows the performance curves of a typical 300-A machine. The efficiency of a transformer welding machine operating on a 40-V load ranges from 80 to 90%. The no-load losses range from 150 to 375 W, depending on the machine. The power factor at a 40-V load is approximately 27% without correction but can be greatly improved by the use of capacitors. The corrective action of capacitors should be based on the normal welding range for which the machine is used. Too much correction may be as bad as none. The figure also shows the difference in power factor for a transformer welding machine with and without capacitor correction

There are several disadvantages to transformer power sources. They operate on single-phase input power, which tends to unbalance utility power lines unless a sufficient number of ac transformer welding machines are used and balanced to the line. In addition, a limited number of types of covered electrodes are available for alternating current.

The maintenance expense of transformer welding power sources is the lowest of any type of welding machine. The use of alternating current reduces the problem of arc blow on complex weldments. Therefore, for many manual shielded metal arc welding applications, the ac transformer power source is the best selection.

10-5 RECTIFIER WELDING MACHINES

Direct current is used for welding with more processes and for many more applications. By means of a rectifier, alternating current is changed to direct current. The rectifier is a device that conducts current easier in one direction than the other. The diode vacuum tube was used for many years in radio power supplies to produce direct current. Six vacuum-tube rectifiers were used in the first rectifier welding machine, which was developed in the mid-1930s. This early welding machine, called a Weld-O-Tron, which had only a 75-A rating, is shown in Figure 10-24. For higher-current output, solid-state rectifiers were developed. The welding industry adopted the dry disk rectifier, which employs a layer of semiconductor such as selenium between adjacent plates. Selenium rectifiers were used in many early rectifier welding power sources. Today the silicon diode rectifier is used for most welding machines.

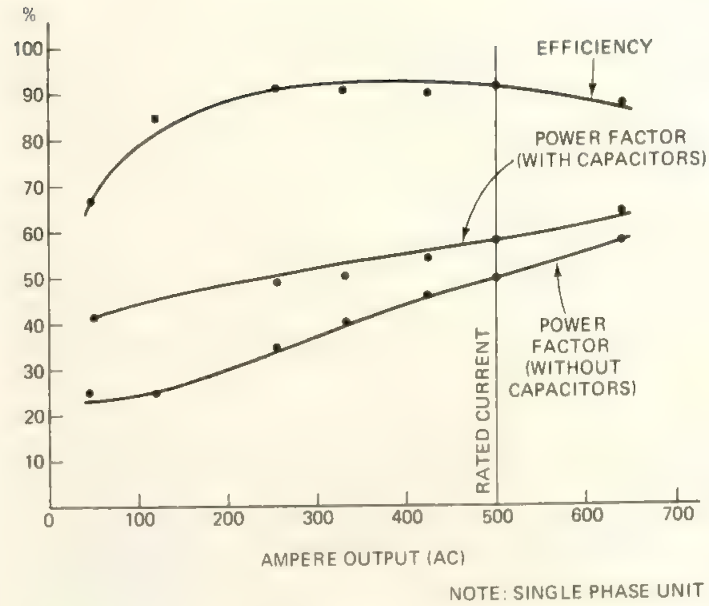
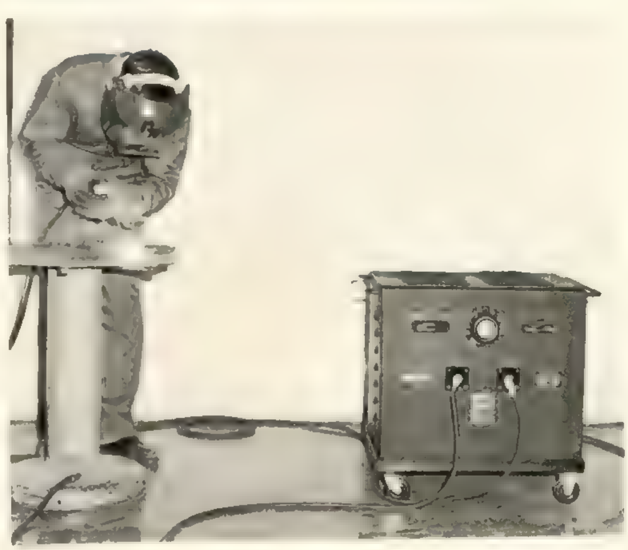


FIGURE 10-23 Performance curves of a transformer welding machine.

Silicon diodes are made of thin wafers of silicon that have small amounts of impurities added to make them semiconductors. The wafers are specially treated and assembled in a case for mounting in welding machines. Figure 10-25 shows a typical power silicon diode. The internal parts, in an exploded view, are shown in Figure 10-26.

Electrical circuits that utilize rectifiers to change alternating current to direct current are well known. No matter what type of rectifier is employed, the results will be essentially the same. The smoothness of the direct-

FIGURE 10-24 First rectifier welding machine.



current output depends on the rectifier circuit that is used. Figure 10-27 shows basic rectifier circuits. The simplest rectifier circuit, known as a half-wave rectifier, will allow only the positive half of each sine wave through and blocks the negative half of the cycle. Single-wave ac input and the half-wave-rectified dc output are shown by the top diagram. This rectified direct current will be very rough, rising from zero to peak voltage, back to zero, then pausing and rising again. This wave shape would be unsuitable for welding. A filter is necessary, but these become large and expensive at power-line frequencies. A design that provides a smoother output utilizes four rectifiers instead of one, known as a full-wave rectifier. This is shown by the second line. The output is considerably smoother but still not satisfactory for most welding applications. When the machine must operate on single phase, the only way to smooth the output is by the use of inductors in series and capacitors across the dc output of the rectifier circuit. These will smooth the roughness or ripple of the direct-current output.

One of the disadvantages of the transformer power source is the fact that it operates only on single-phase ac power. To provide smoother direct-current output, three-phase ac input is used. This provided smoother dc out-

FIGURE 10-25 Silicon power diode rectifier.

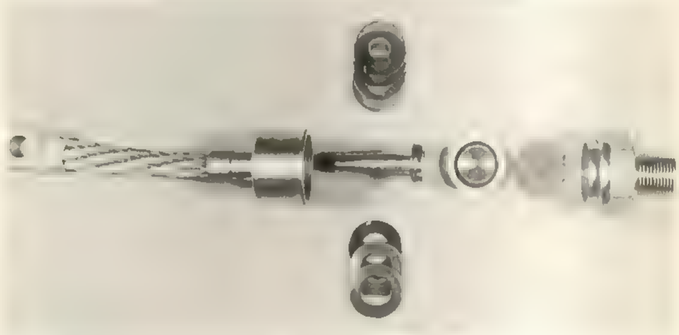


FIGURE 10-26 Silicon diode rectifier parts.

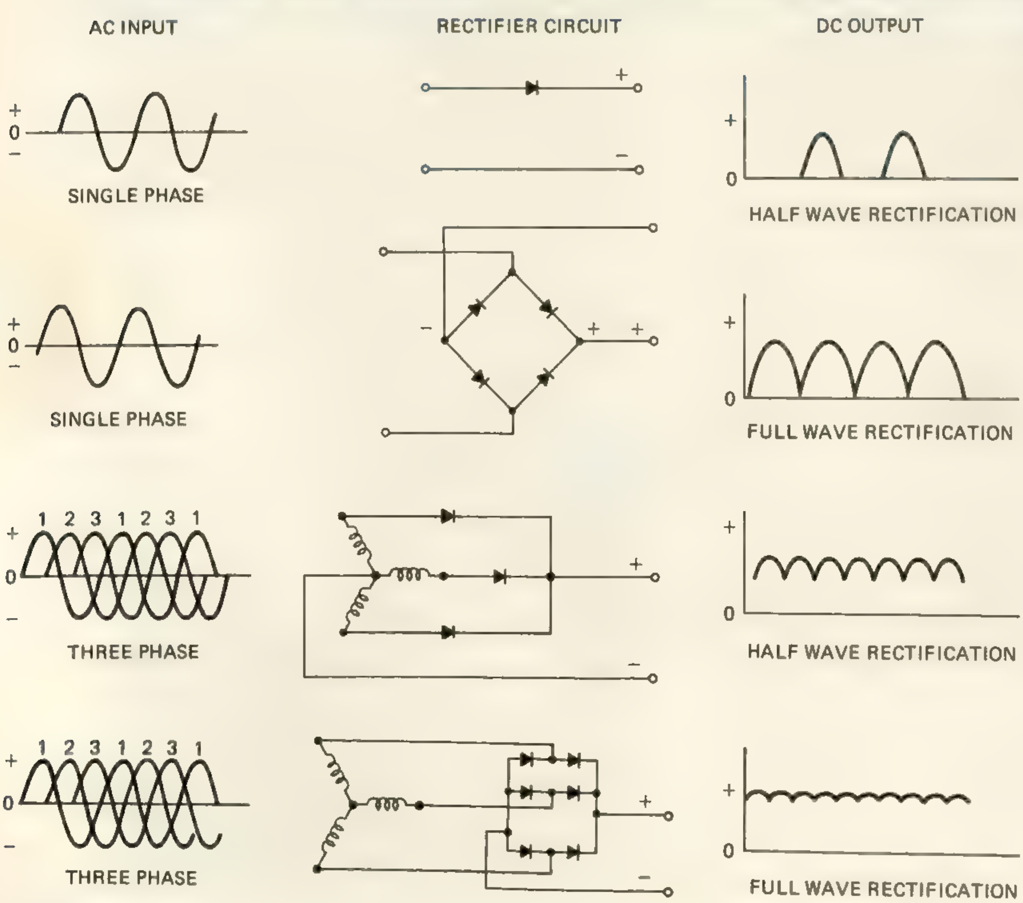


FIGURE 10-27 Basic rectifier circuits.

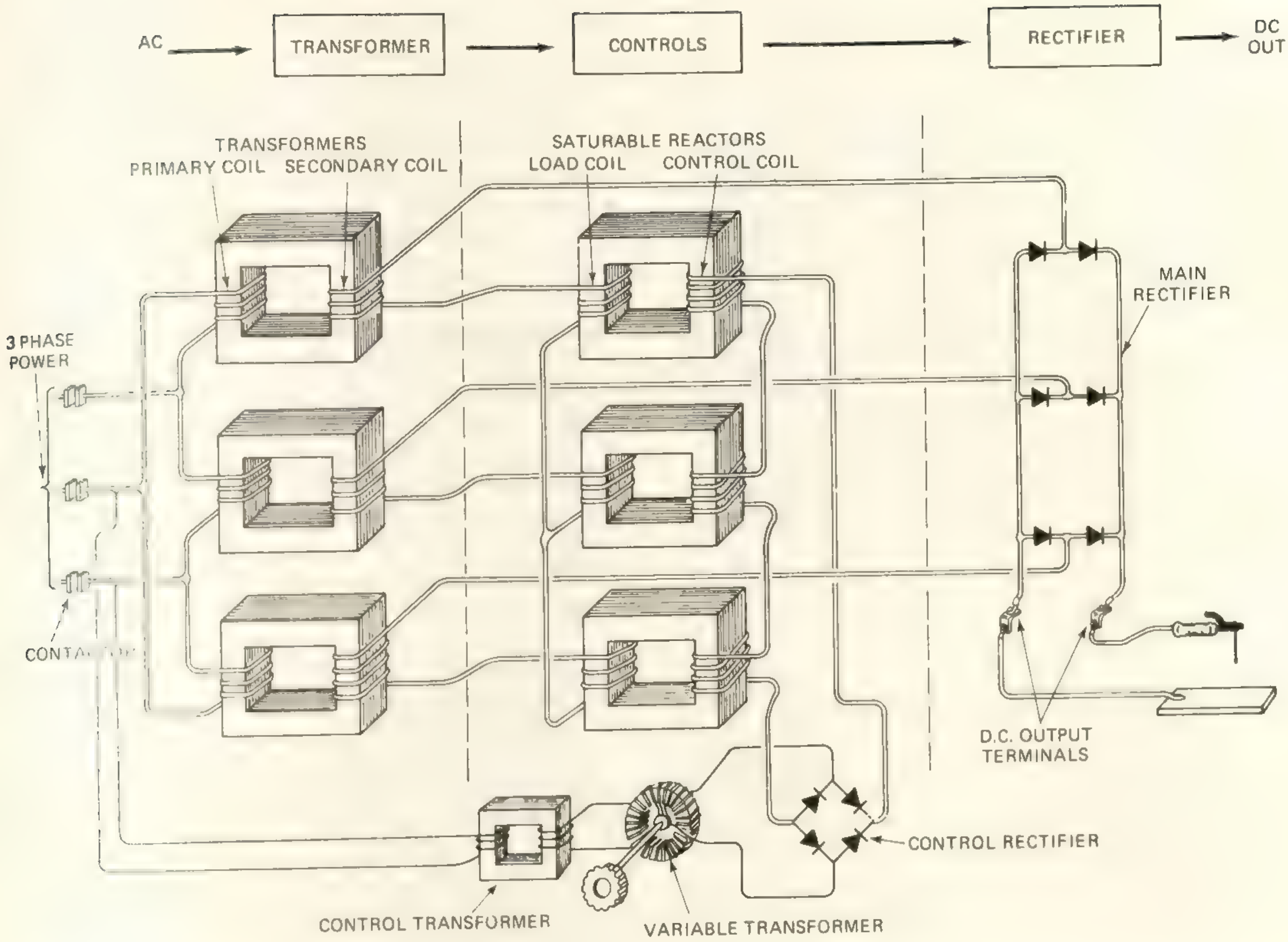
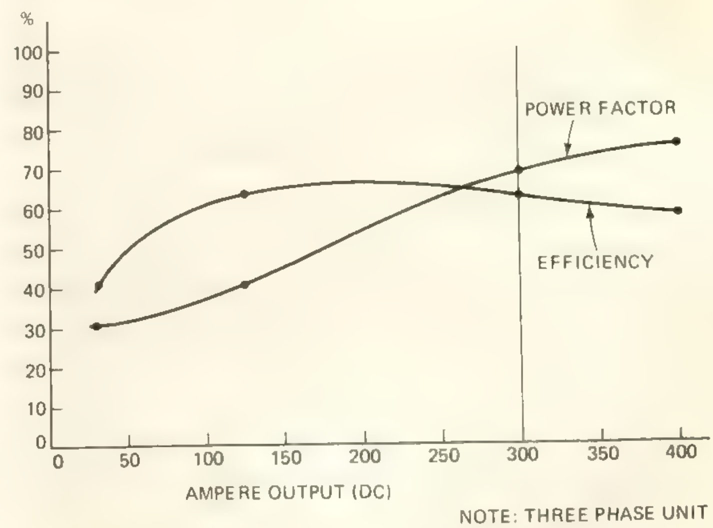


FIGURE 10-28 Rectifier welding power source.

put, as shown by the third line. By using twice as many power diodes, it is possible to further smooth out the dc output of a three-phase machine. This is accomplished by using a full-wave rectifier, as shown by the bottom line. Most industrial rectifier welding power sources use three-phase input and full-wave rectification to provide smooth dc output. These machines provide a balanced load on the three-phase power line, which is an advantage over the single-phase transformer machines. Some small rectifier welding machines do operate on a single phase. These machines have a filter circuit but do not provide an arc that is as smooth as the three-phase machines.

A simplified version of a modern rectifier welding power source is shown in Figure 10-28. This type of machine can have drooping static volt-ampere characteristics or relatively flat or constant-voltage output characteristics. The output characteristics depend on the inductance in the control circuitry. This basic design is used for most industrial rectifier welding power sources. The performance curves for this type of machine are shown in Figure 10-29.

FIGURE 10-29 Performance curves of a rectifier welding machine.



10-6 PROGRAMMABLE, PULSING, AND SPECIAL WELDING MACHINES

The technology of welding is advancing and there are continuing improvements to make it a more precise process. The welding industry is responding by providing machines with improved arc starting characteristics and improved arc stability, which produce less weld spatter, and improved weld finish. The newer machines are more efficient and are lightweight, small, and portable. Machines are now available that change welding parameters while welding and pulse the welding current. The new machines have greater capability than the older ones.

The rapid development of solid-state electronic components is helping to satisfy these needs. The availability of high-powered solid-state components (rectifiers, transistors, thyristors, etc.) is contributing to the development of power sources with capabilities for precision welding. The result of these developments has been the introduction of welding power sources with inverter design, square-wave balanced output, programmable and preprogrammed capabilities, variable polarity output, pulsing current output, and others.

The introduction of the high-powered silicon diode made the transformer–rectifier power source very popular. It also allowed for automatic control of the output based on timer-operated programmers. Before describing these newer machines, it is necessary to have knowledge of the electronic devices being employed.

Solid-State Devices

The power electronics industry has advanced at a tremendous rate in the last few years. It has introduced solid-state components that include rectifiers, high-speed switches, oscillators, choppers, amplifiers, and detectors. The solid-state components are rugged, small, and require very little power to operate but control high currents. The welding industry is using them to provide solid-state contactors, solid-state timers, line-voltage compensation, high-current rectifiers, and control circuits. These newer devices are extremely rugged, fast, less heat sensitive, more powerful, and are more cost-effective.

The beginning of the solid-state revolution for welding machines was the silicon diode. The silicon diode, along with the saturable reactor, brought power electronics to the welding industry. The diode is a two-element device used in a rectifier circuit, and it was described in the section on transformer–rectifier welding machines.

The transistor was the next solid-state device to be employed in welding machines. The transistor is a three-layer semiconductor device which uses a small amount of current to produce a large change in voltage, current, or power. The transistor is very similar to the diode except for the addition of a very thin element called the "base" which is placed between the emitter and the collector. It can be considered the same as two diodes working together. The output of the transistor is controlled by applying a small low-current signal to the base, which in turn controls a large amount of current through the transistor. Transistors are normally used in control circuits, where small signals control large outputs.

The next solid-state device to be used in welding machines was the silicon-controlled rectifier (SCR). This semiconductor is a four-layer device that can be triggered or turned on by a low pulse signal to the gate lead. Once it is triggered, it does not require additional control current. The silicon-controlled rectifier blocks current attempting to flow in either direction between the anode and cathode under normal circumstances; however, when a signal is applied to the gate lead the SCR begins to conduct current. The SCR will continue to conduct current after the gate signal stops as long as the power current continues to flow. If the power current is turned off, the SCR will require another gate lead signal to start current flowing again. One thing that turns off the power current is when it goes to zero in a sinusoidal ac waveform.

An SCR can be used to control output current. This is done by varying the point or angle, in the alternating-current cycle, when the pulse is applied to trigger the SCR. This is known as phase-angle control and is used to turn on or trigger the SCR to become conductive at a specific point on the ac cycle. Moving the gate pulse signal will trigger the SCR at any point of the ac sine wave. Any or all of a cycle can be made conductive, allowing current to flow for that portion of the half-cycle. When the SCR is not triggered, no current passes and it is like an open switch. Triggering the SCR at the proper point on the sine wave can make it operate as a switch or solid-state contactor. SCRs have very high current ratings and can be used to pass the total welding current. Silicon-controlled rectifiers are sometimes called thyristors.

The next electronic device utilized in the newer power sources is the integrated circuit (IC). These are complete electronic circuits of miniature components encapsulated in plastic with many leads. Many different types of electrical circuits are available as integrated circuits. Since they are very small they utilize low voltages and low currents. They are normally mounted on printed circuit boards, known as PC boards. By mounting the proper integrated circuit and other components on these insulated boards and by connecting them together, extremely complex devices can be made. Each printed circuit board plugs into a socket for ease of replacement. PC boards are the control circuits for most of the newer welding machines. They are also used to control wire feeders and motion devices. Figure 10-30 shows a typical PC board having a number of integrated circuits. Figure 10-31 shows the graphic symbol for these and other electronic or electrical components.

Welding machines that employ power electronics controlled by PC boards offer many advantages. They control static characteristics of the power source, including waveform, and can change the welding characteristics to provide a soft arc or a harsh digging arc by a simple dial change. They provide electronic power contactors instead of mechanical contactors, which eliminates moving parts. They provide power-line voltage compensation and can handle variations of power-line voltage of up to 10% with only 2% variation of the output. They are used as a balance control to change the amount of ac positive cycles versus ac negative cycles for ac gas tungsten arc welding. They provide pulsed current of different frequencies and different wave shapes. They provide time-base programming by changing welding current output, sloping up or down, as required. They are used for remote control, which allows the use of miniaturized potentiometers on welding guns. They greatly simplify all control aspects of semiautomatic and automatic welding. They also allow the control of welding equipment by computers for precise programming.

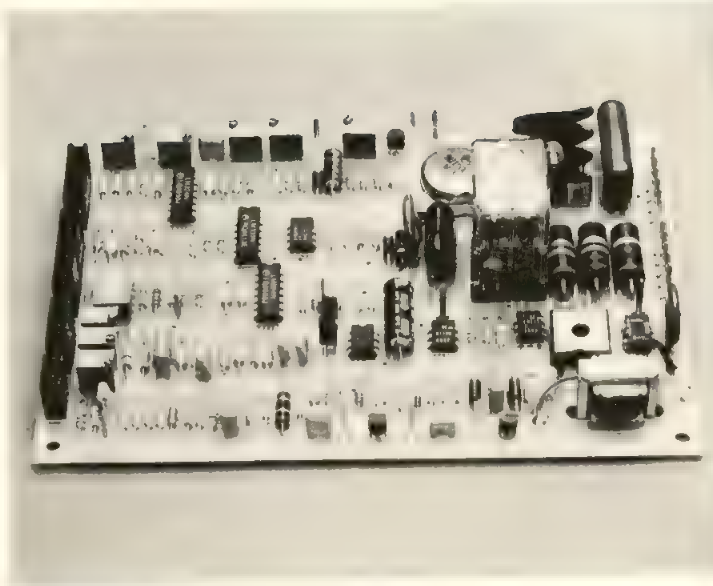


FIGURE 10-30 Printed circuit board.

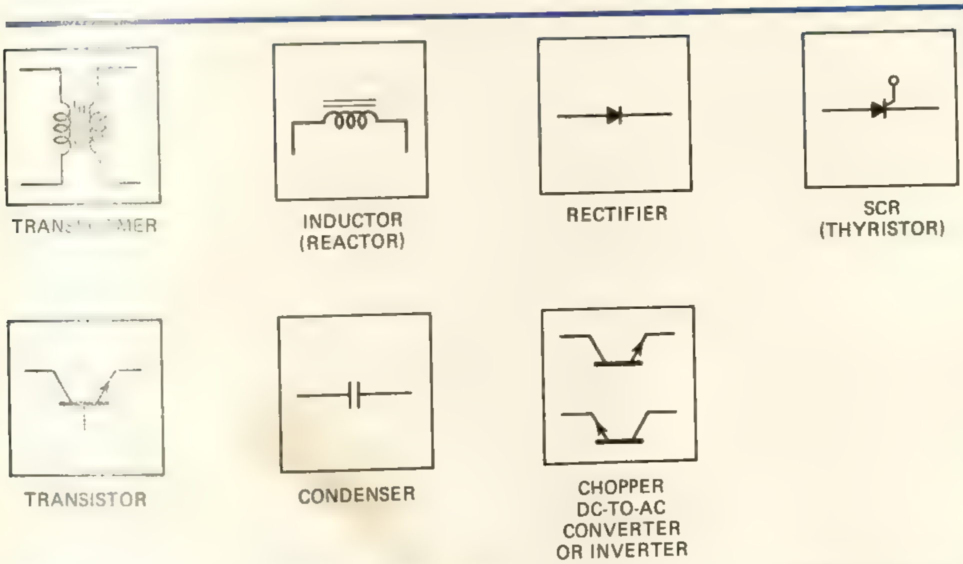


FIGURE 10-31 Symbols of electronic components.

Solid-State Power Sources

The major breakthrough in the introduction of electronic devices for welding power sources was the transformer power source that used silicon diodes and the saturable reactor for current control. This was described previously and is shown in Figure 10-32, which also shows the waveform.

The transformer-rectifier machine almost immediately followed and is shown in Figure 10-33, which describes the electrical control of a transformer-rectifier welding machine by means of a saturable reactor.

This was soon followed by the solid-state ac phase-angle-controlled transformer-rectifier power source. Silicon-controlled rectifiers (SCRs) or thyristors operate downstream from the power transformer and perform the rectification function. However, instead of being conductive full time as with the silicon diode, they operate only a partial cycle based on the phase angle of the ac current. The SCR gate is turned on at the appropriate angle to allow more or less current to flow. By turning on the SCRs full time, the maximum current will flow. By decreasing the ignition angle, a lesser amount will flow. This provides for continuous control of the output of the power source (Figure 10-34).

Another development was the power source with dc control by power transistors. This type of power source uses a power transformer and solid-state silicon diode rectifiers. This is followed by a bank of transistors in parallel acting as series regulators. This is followed by a bank of capacitors for smoothing out the ripple on the dc current. This machine requires substantial power to

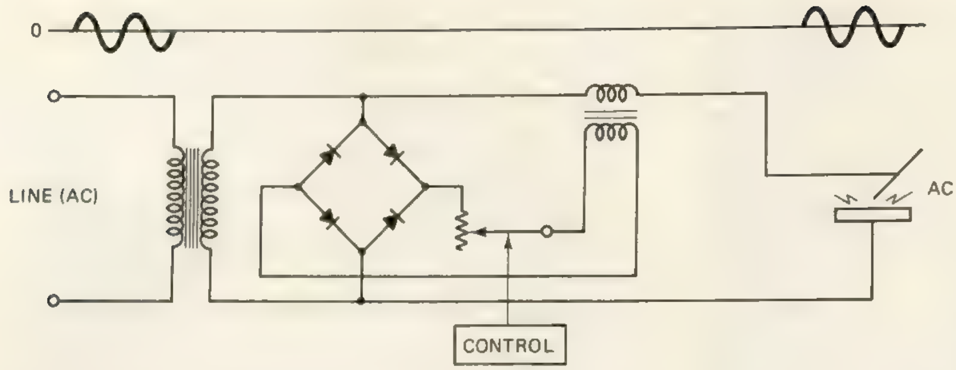


FIGURE 10-32 Saturable reactor control of transformer power source.

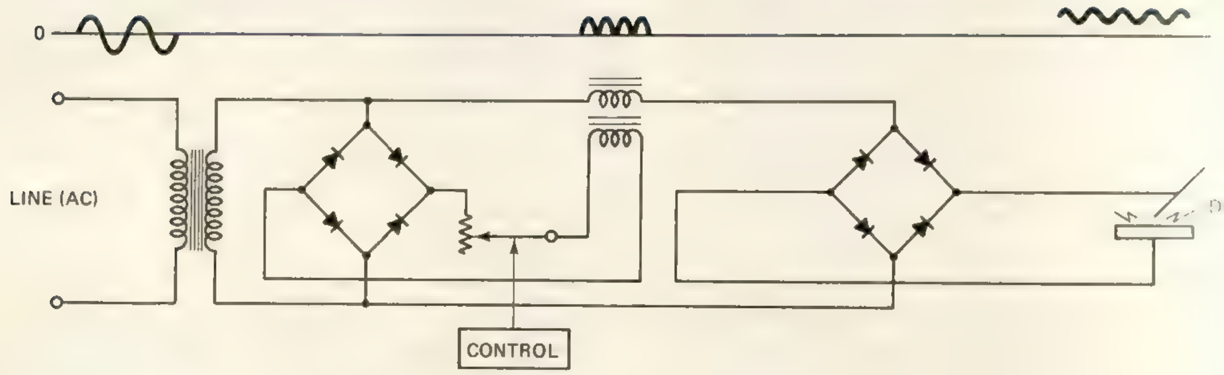


FIGURE 10-33 Saturable reactor control of transformer-rectifier power source.

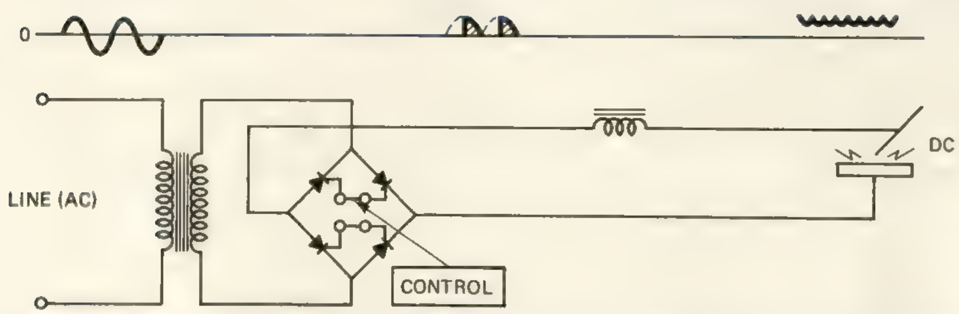


FIGURE 10-34 Thyristor (phase angle) control and rectifier.

be dissipated in the transistor banks, and in many cases water cooling is employed. This power source can be precisely controlled to provide specific static and dynamic characteristics of the power source. It will provide a specific welding program controlled by a solid-state controller. A schematic of this type of power source is shown in Figure 10-35.

Inverter Power Sources

The latest type of power source utilizes the inverter, which provides a lightweight compact unit (Figure 10-36). In this type of power source, the power from the line is first rectified to pulsing dc. This then goes to a high-frequency oscillator or chopper, which changes the dc to high-voltage high-frequency ac in the range 5 to 30 kHz. The output of the chopper circuit is controlled in accordance with welding procedure requirements. The high-frequency ac is then transformed down to the operating welding voltage. The secret of the inverter is the use of a small lightweight transformer, since transformers become smaller as frequency increases. The high-frequency ac current is then rectified with silicon diodes to provide direct-current output at normal welding current and voltage. The inverter type of power source has become economically feasible due to the availability of high-current, high-speed solid-state electronic components available at reasonable cost. Inverter power sources are about 25% the weight of a conventional rectifier of the same power capacity, and about 33% of the size. They provide a higher electrical efficiency, a higher power factor, and a faster response time. They can be used for the majority of arc welding processes.

There are two variations of the inverter power

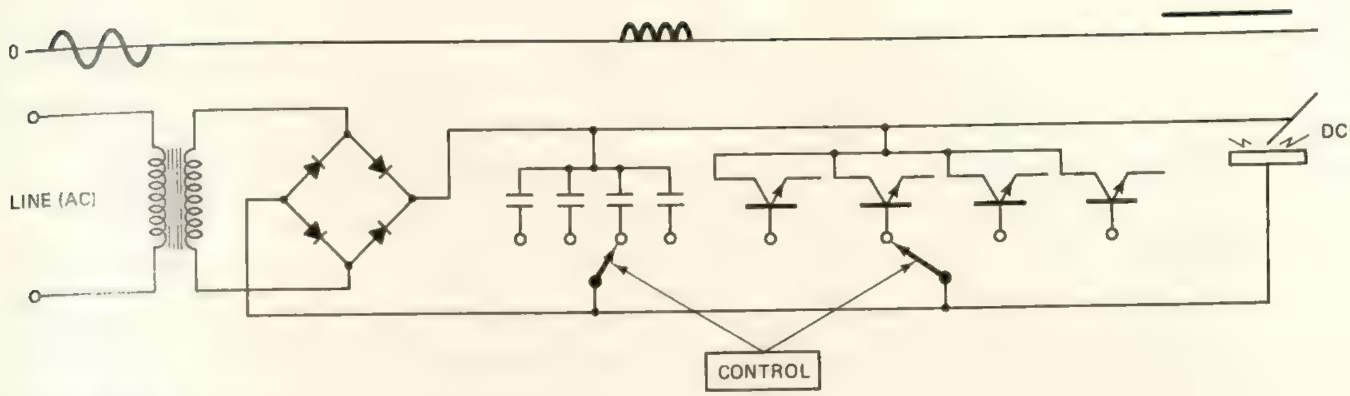


FIGURE 10-35 Power source with power transistor control.

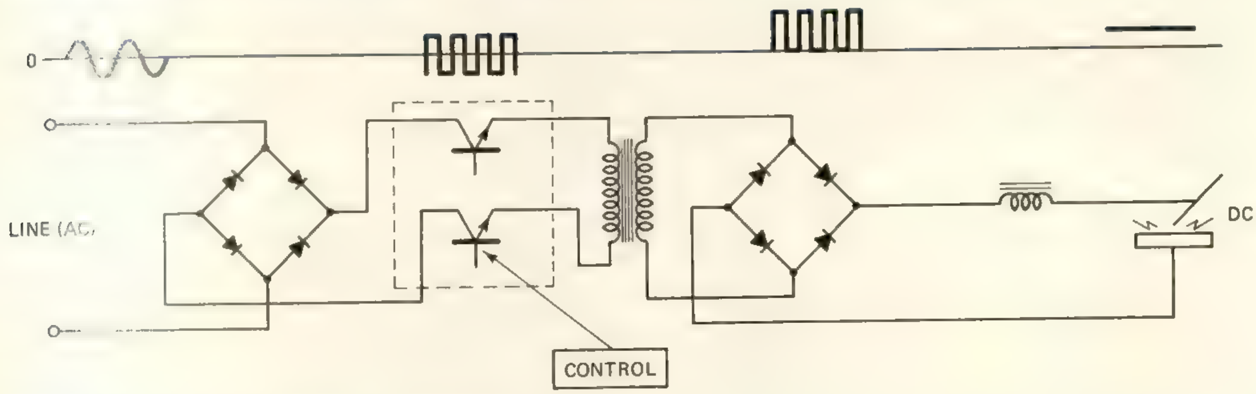


FIGURE 10-36 Inverter design power source.

source, depending on the frequency of the chopper. Low-frequency machines use a frequency in the audible range, usually 10 kHz or lower. This results in a noisy machine objectionable to the welder. Higher frequencies, 15 kHz or higher, avoid the audible noise problem but require faster acting electronic components. Figure 10-37 shows an inverter-type portable power source for gas metal arc welding. These basic circuits for welding power sources can be put together in different ways to provide specialized welding power sources for different requirements.

FIGURE 10-37 Portable inverter power source for SMAW.

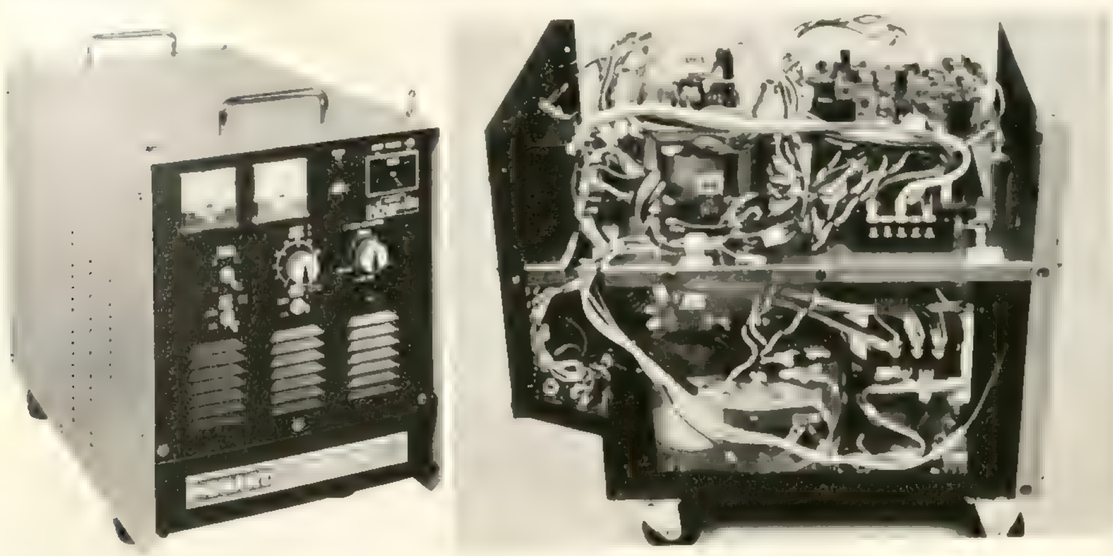
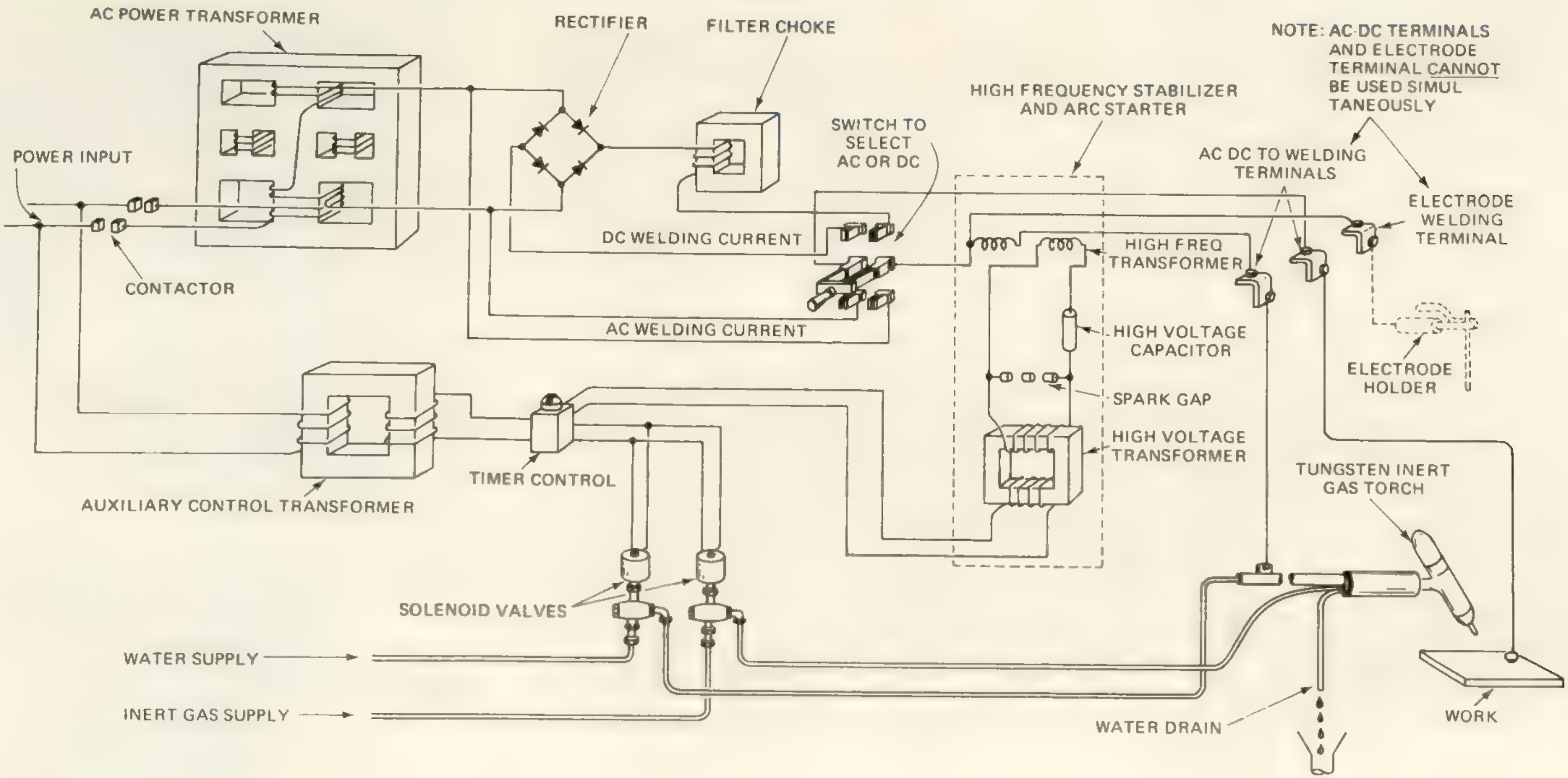


FIGURE 10-38 Simplified diagram of ac–dc power source for GTAW welding.



Gas Tungsten Arc Welding Machines

As GTAW became popular, special power sources were developed for the process. These machines eliminated the dc component in the welding circuit usually found in conventional power sources. The characteristic output curve of the machines were made much steeper, so that changes in arc length would have minor effect on welding current. Most units included a high-frequency oscillator to improve arc stability when welding with alternating current and to provide arc starting without touching the electrode to the work. A simplified diagram of this machine is shown in Figure 10-38. The high-frequency stabilizing current is superimposed on the welding current to ionize the arc gap when starting the arc. The high-frequency current provides ionization of the arc gap for ac welding so that as the welding current goes through zero, the arc would be reestablished instantaneously. This improved arc stability and eliminated rectification in the arc at each half-cycle. The high-frequency oscillator consists of a high-voltage transformer, a spark gap, high-voltage capacitors and resistors, and a coupling coil. The circuit diagram is shown within the dashed lines in Figure 10-38. The high-frequency current is a rather broad-based signal with a fundamental frequency of about 2 MHz. This spectrum is very rich in harmonics with 20-MHz components. The frequency is determined by the charging time of the high-voltage capacitor and by the 50- or 60-Hz line frequency. The high frequency can be radiated by the welding leads or conducted by power lines. Proper shielding is required. Proper installation of the equipment is necessary to avoid radiation, which might interfere with aviation communications and broadcast and TV stations. The length of the welding leads and their arrangement has an effect on reducing high frequency at the arc. Combination ac–dc welding machines for gas tungsten arc that can also be used for shielded metal arc welding became popular. Since these machines produce both ac and dc, they utilize single-phase power input. Recently, machines have been designed with three-phase input for better power-line balancing. Extra terminals are provided for the gas tungsten arc welding torch as well as for the shielded metal arc welding lead. Most machines include solenoid valves for controlling shielding gas and cooling water. Machines of this type are now available with programmers which can provide simple-to-complex programs, depending on the welding application. Some programmers include motor speed controls for setting the speed of travel mechanisms, such as orbital tube heads. Many programmers also include low-frequency pulsing capabilities. A programmable machine with various levels of programmers is shown in Figure 10-39.

A more recent machine using the inverter and different levels of programming is shown in Figure 10-40. This is a 150-A machine designed for GTAW and plasma

FIGURE 10-39 Programmable ac–dc power source for GTAW.

FIGURE 10-40 150-Ampere inverter power source for GTAW welding.

welding with a three-phase input. The machine provides power down to 1 A with a very fast response time of 1 millisecond and less than 1% ripple. This machine is rated with an output voltage of 16 V, hence is used only with the gas tungsten arc or plasma arc welding processes. The volt-ampere static characteristics are shown in Figure 10-41, and the very fast pulsation response time is shown in Figure 10-42. Different programming is available, depending on complexity of the job. The three more popular programmers are shown in Figure 10-43.

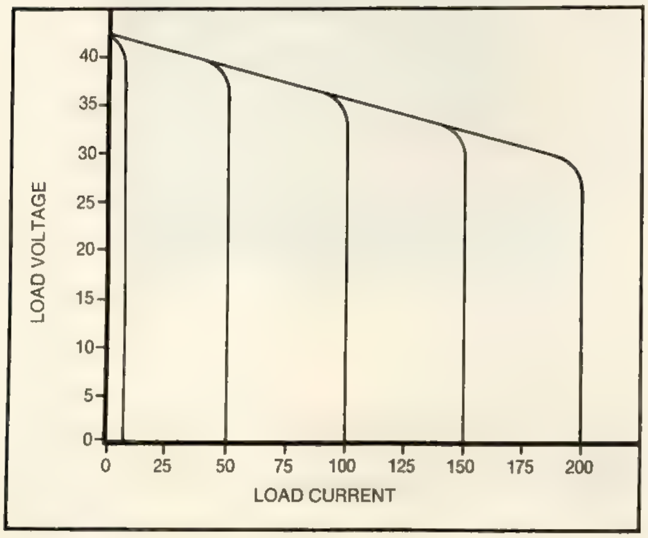
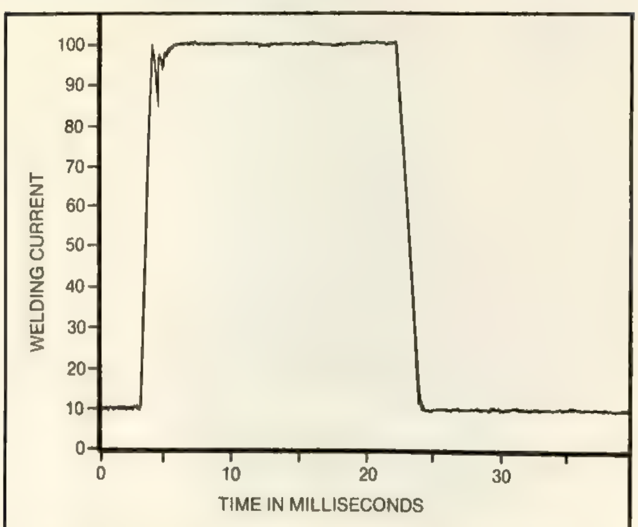


FIGURE 10-41 Volt-ampere static characteristic curve for 150-A inverter power source.

FIGURE 10-42 Pulsation response time for 150-A inverter power source.



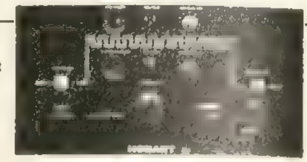
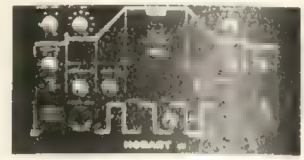
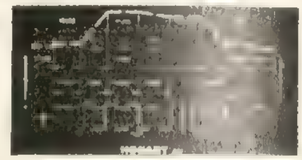
DISTINCT CONTROL FUNCTIONS	APPLICATIONS	
Prepurge; pulsation and arc spot timer	Manual welding, TIG spot welding with or without pulsation. Used when slope control is not required.	
Upslope, downslope and pulsation weld time	Controlled slope rate and pulsation for manual or automatic welding. For pipe welding, thinwall tubing, and difficult to weld application and materials.	
Precision upslope, downslope, pulsation and weld taper with direct reading dials.	For machine TIG welding where pulsation and precision programming of upslope, downslope, and weld taper are required. Designed to perform the most difficult TIG welding jobs.	

FIGURE 10-43 Popular programs for gas tungsten and plasma arc welding.

Square-Wave Power Sources

The conventional ac sine-wave output has an arc outage or arc extinction range as the welding current passes through zero (Figure 10-44). This reduces arc stability with the gas tungsten arc welding process and to some degree with the plasma arc and submerged arc welding process. This problem is exaggerated by many electrically controlled power sources which have a distorted sine wave that goes through the zero line even slower. To overcome the arc extinguishing–restriking problem, a square-wave ac output power source was developed. The square-wave output form can be utilized by either the conventional constant-current type or by the constant-voltage type. In either case the time for switching from positive to negative, or negative to positive current pulse, is on the order of 50 to 150 microseconds; thus the arc is reestablished with the opposite polarity before thermal electron emission decays to the point that the arc is difficult to restart and is unstable.

Power electronics can be used to vary the positive and negative output of the machine. The area above the zero point on the curve, that is, the direct-current positive area, and the area below the curve, the negative area, can be equalized or balanced. A power source developed specifically for gas tungsten arc and plasma arc welding provides a square-wave output form, but also allows a balance or imbalance between the straight-polarity and reverse-polarity half-cycles of each cycle. In welding aluminum it has been established that the electrode negative (straight-polarity half-cycle) gives maximum penetration, whereas the electrode positive (reverse-

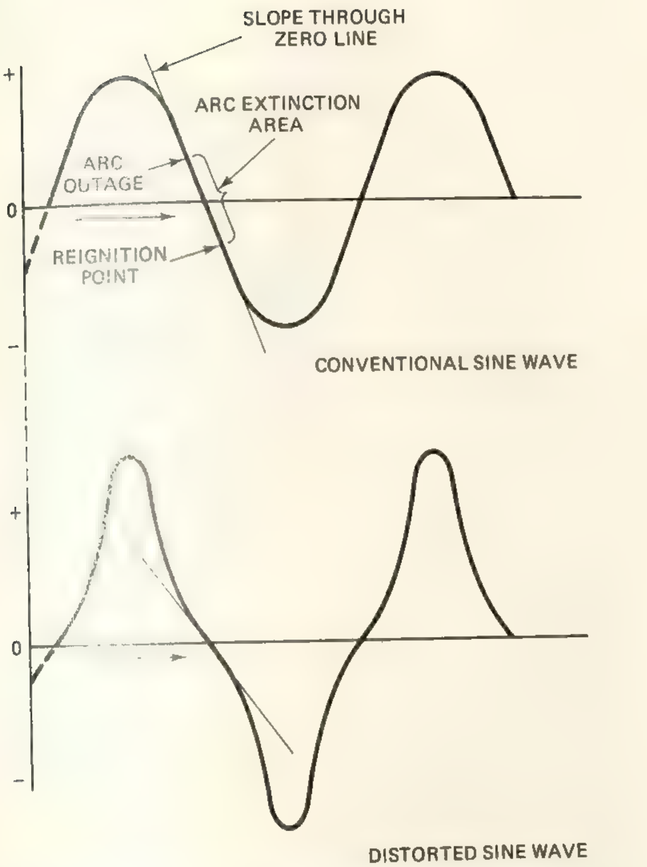


FIGURE 10-44 Current waveforms for ac welding.

polarity half-cycle) provides for the cleaning action. It is advantageous to provide the most-straight-polarity half-cycle, and this is possible as shown in Figure 10-45. This machine also has programming ability and encloses high-frequency oscillator plus gas and water valves.

Square-wave CV welding with alternating current has been used for narrow groove submerged arc welding. This has proved to be more efficient than welding with conventional sine-wave ac current.

Variable-Polarity Power Source

Research involving plasma arc welding of aluminum established the fact that very little electrode positive or reverse-polarity half-cycle is required for cleaning and that maximum work can be performed if the straight-polarity weld cycle is maximum.[4] A special variable-polarity type of power source with square-wave output has been designed for this application. Figure 10-46 shows the waveform for this machine. In a sense it is almost like two machines, one with straight polarity and one with reverse polarity connected by means of an instantaneous electronic switch. A machine of this type is shown in Figure 10-47. This is a SCR type of power source with extremely fast reaction time. It includes the auxiliary devices, programmers, gas valves, and so on. This machine will make welds that provide water-clear x-rays of aluminum made with the plasma keyhole process. It is used primarily for automated applications and is able to weld ½-in-thick aluminum in one pass with 100% penetration.

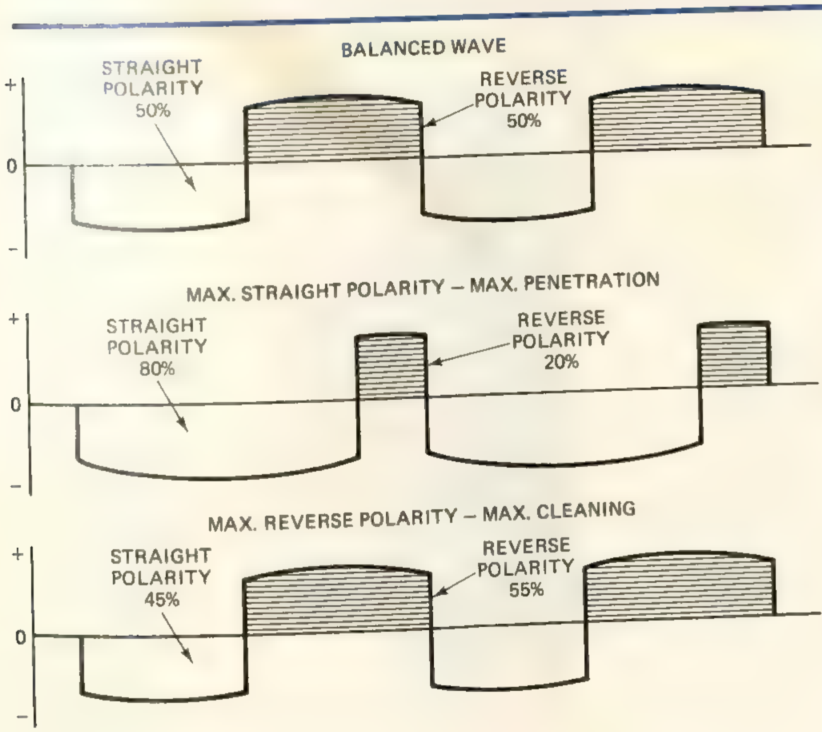


FIGURE 10-45 Square-wave output: balanced and unbalanced.

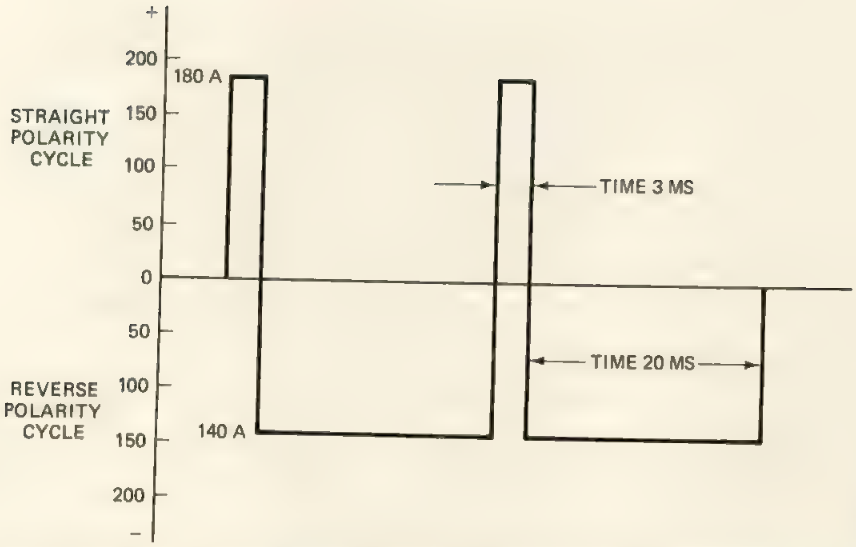


FIGURE 10-46 Waveform of variable-polarity power source.

FIGURE 10-47 Variable-polarity power source.

Synergic Welding

The gas metal arc variable-frequency pulsing system, known as synergic welding, makes use of a solid-state type of power source.[5] There are basically two types of synergic power source-wire feed systems. In one case the frequency of pulsing remains the same, but the maximum or peak pulse current and the background current vary. In the other case the frequency of the current will change and the background-to-pulsing current ratio remains the same. In either case the wire feeder must match the output of the power source. In addition, the power source will have a subprogram which provides the pulse waveform for each pulse. This geometry will change with different applications. These are based on the filler metal type, filler metal size, and the welding gas atmosphere. The inverter-type power sources have proven superior to SCR types because of the high frequency of pulsing, the square wave required per pulse, and the ease of control by means of microprocessors. A microprocessor determines the waveform geometry of each pulse. Two different types of power sources are available. Figure 10-48 shows a constant-voltage machine with four preset pro-

FIGURE 10-48 Mega pulse.

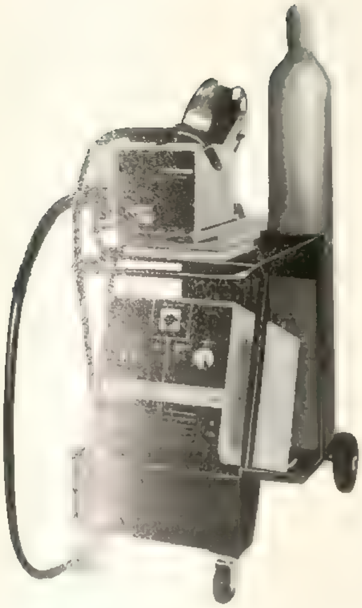


FIGURE 10-49 Ultra arc.

grams. The operator need only select the desired program and by means of the wire feed speed control can adjust the machine from minimum to maximum output. An arc length control adjustment controls arc voltage. The peak current, peak current time, background current, and frequency are automatically adjusted by the computer program. This machine can also be used as a standard constant-voltage power source without pulsing. Figure 10-49 shows a constant-current machine with nine programs selected by a keypad. One knob adjusts the average current from minimum to maximum. Another adjusts the arc length or voltage. The computer of the power source and its matched wire feeder automatically adjust wire feed rate, pulse frequency, high pulse current, and high current time and background current. This machine can also be used as a standard constant-current power source without pulsing.

It is expected that solid-state power sources will become the dominant type as welding procedures demand more precise control to produce welds of higher quality.

10-7 MULTIPLE-OPERATOR WELDING SYSTEMS

The multiarc welding system utilizes a high-current constant-voltage power source to supply power for many welding arcs (Figure 10-50). This differs from the conventional single-operator power supply system in which an individual welding power source is required for each welding arc. The multiple-operator system is used when there is a large concentration of welding arcs in a relatively small area. The system was originally used in shipyards during World War II and has been popular at construction sites for powerhouses, refineries, chemical plants, and for some manufacturing operations. One of the major advantages of the multiple-operator system is the lower capital investment required per welding arc. This is based on lower cost of installation as well as the cost of the power source and of the individual welding stations. By the use of the multiple-operator system it is not necessary to have primary power at each welder's station.

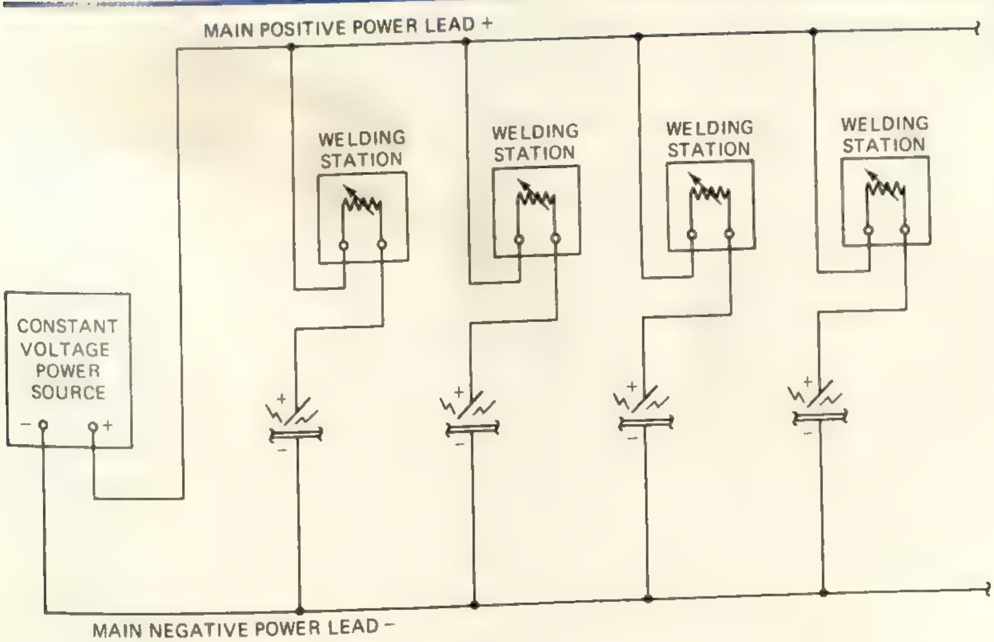


FIGURE 10-50 Multiple-operator system.

The basis of the multiple-arc system is *load diversity* and *operator factor* or duty cycle. The multiple-operator system uses a single large welding power source with a capacity considerably smaller than the total capacity that would be required when using single-operator power sources.[6] Load diversity means that in a large group of welders only a small percentage will be welding at any one time. This is because of the normal welder operator factor or duty cycle. The operator factor is the percentage of time that the welder is actually welding against the total or paid time. The operator factor or duty cycle can vary from 10 to 50%, depending on the type of work. Pipe and structural welding tends to be on the low side. The diversity factor is related to average duty cycle and the laws of probability. It is not expected that all the welders will start to weld at precisely the same time.

The relationship between these factors—the number of arcs to be used, the welding current, and the needed available power—is shown by the following formula:

$$\text{total power required} = \text{number of arcs} \times \text{average amperes each arc} \times \text{average duty cycle each arc}$$

To determine the number of arcs that can be employed when the available power is known, the formula can be restated as follows:

$$\text{Number of arcs} = \frac{\text{total power available}}{\text{average amperes each arc} \times \text{average duty cycle each arc}}$$

To utilize this formula it is necessary to determine the amperes that will be used at each arc. The current required at an arc can be estimated by referring to Figure 10-51, which shows the average current required based on the welding process and the size of the electrode employed. This chart shows data for shielded metal arc welding, gas tungsten arc welding, air carbon arc cutting and gouging, and stud welding. It is assumed that a normal duty cycle would apply. This excludes stud welding which utilizes much higher currents, but the arc duration is normally less than 2 seconds. These processes utilize direct-current electrode positive with the exception of gas tungsten arc welding, which utilizes electrode negative.

With these data it is possible to determine the number of welding arcs that can be used with a specific-size power source. The power sources available for multiple-operator welding range from 500 to 1500 A and larger. Machines can be paralleled to obtain higher currents for larger installations. The data shown in Figure 10-52 are based on the available power of 1000 A at a 100% duty cycle and with the provisions of a 50% overload of not over 2 minutes.

Power sources used for multiple-operator systems have a maximum open-circuit voltage of 80 V and a load voltage of approximately 75 V at rated output. Motor generators were previously used as power supplies; however, the silicon diode three-phase rectifier welding machine is currently used. Machines of this type have an operating efficiency of approximately 90%. These machines do not have controls to change either current or voltage and for this reason are used only with multiarc systems.

A welding station, or grid, is required at each arc. The welding stations consist of switches and resistance grids, which are in series with the arc. By means of switches the amount of resistance in series with the arc can be adjusted to provide the correct current for that particular arc. Since the normal voltage across a shielded metal arc is 25 V it would follow that 55 V would be dropped across the resistance grid of the welding station. If 200 A current is used for welding, this would amount to 11,000 W of heat produced in the welding station.

In some welding stations polarity switches are incorporated so that electrode negative can be used. When dual polarity is required two power sources must be used. The positive pole of one and the negative pole of the other power source are connected to the common lead or

Size of Electrode, Carbon or Stud (Dia.)		Average Current Required			
in.	mm	SMAW DCEP or DCEN	GTAW DCEN	AAC DCEP	SW–2 Sec. Max.–DCEP
0.035	0.9	–	50	–	–
0.045	1.1	–	75	–	–
1/16	1.6	–	110	–	–
3/32	2.4	75	180	–	–
1/8	3.2	100	235	–	–
5/32	3.9	150	300	150	–
3/16	4.8	200	400	200	–
7/32	5.6	275	450	300	300
1/4	6.4	350	500	400	350
5/16	7.9	–	–	500	400
3/8	9.5	–	–	600	500
1/2	12	–	–	1200	600
					900

FIGURE 10-51 Average current required for electrode size, by process.

Ampere Per Arc	Duty Cycle of Welders 25%	20%	25%	30%	35%	40%	45%	50%	55%	60%
50	132	100	80	66	56	50	44	40	36	32
75	88	66	56	44	38	32	28	26	24	22
100	66	50	40	32	28	24	22	20	18	16
125	56	40	32	26	22	20	16	16	14	12
150	44	32	26	20	18	16	14	12	12	10
175	38	28	22	18	16	14	12	10	10	8
200	32	24	20	16	14	12	10	10	8	8
225	28	22	16	14	12	10	8	8	8	6
250	26	20	16	12	10	10	8	8	6	6
275	24	18	14	12	10	8	8	6	6	6
300	22	16	12	10	8	8	6	6	6	4
325	20	14	12	10	8	6	6	6	4	4
350	18	14	10	8	8	6	6	4	4	4
375	16	12	10	8	6	6	4	4	4	4
400	16	12	10	8	6	6	4	4	4	4

FIGURE 10-52 Maximum number of welding arcs with 1000-A power source.

building frame. Separate conductors are needed for other leads, both of which are brought to the dual-polarity welding stations. In this way either polarity is available. This is particularly advantageous for gas tungsten arc welding. Normally, the systems are set up so that the electrode is positive. The switching arrangement allows for either polarity of welding current and for fine control.

Another advantage of the multiarc system is the volt-ampere characteristic curve presented to the arc (Figure 10-53). This is a straight-line drooping relationship based on pure resistance, which allows for a very smooth arc. The resistance load is a limiting load, and therefore, transients are minimized. The slope of the curve is determined by the amperage setting of the grids, but in all settings it is a straight line rather than the curved line of a single-operator welding machine.

The multiarc system is often used for air carbon arc cutting and gouging. As with the other applications, the duty cycle and current limitations must be observed.

The multiarc system is also used for stud arc welding when the current requirement is normally greater than the requirement for shielded metal arc welding. This can be done since all the components of the system have short-time overload capabilities. The welding power source will provide an overload of up to 50% for 2 minutes maximum. The time cycle for stud welding is usually less than 2 seconds. In view of this, overloads for stud welding can be accommodated.

The cables required for MO systems are extremely large in order to minimize power loss. Cable size should be based on a maximum of 3 V drop per 100 ft. The size of the main conductors from the power source to distribution centers depends on the length and the current carried; normally, a 500 MCM cable is used. This size of cable is larger than flexible welding cable and is therefore not of fine-strand flexible cable design. The heavy cable is used with distribution blocks or tap plugs so that smaller cables can be run to the individual welding sta-

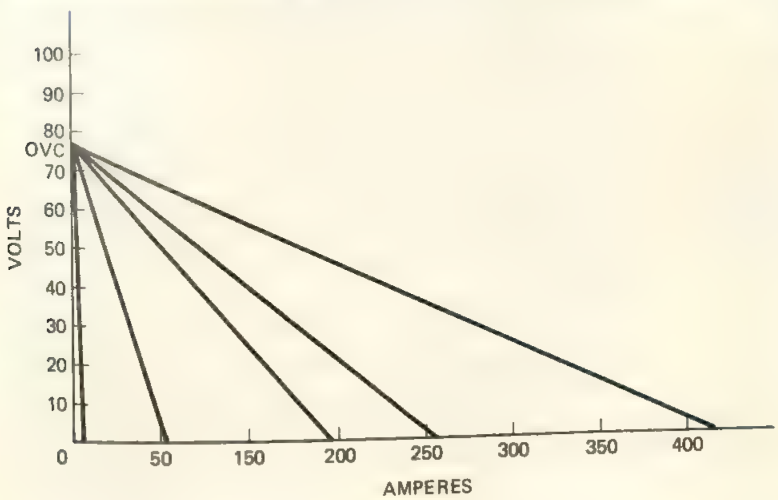


FIGURE 10-53 Volt-ampere characteristic curve of welding station.

tions. From the welding stations to the electrode holder conventional welding cable sizes are used. Standard 115-V ac power is usually provided for auxiliary equipment.

For gas tungsten arc welding special high-frequency attachments are used to avoid touch starting of the tungsten to the work. These are installed at the welding station. The gas tungsten arc process is commonly used for root-pass welding of piping in power plants.

It is common practice in power plants to retain the welding system within the building leaving the heavy conductors permanently installed. In this way, future maintenance welding can be done in any part of the power plant.

The multiple-operator or multiarc system has specific advantages and it is necessary to make calculations to determine the installation cost with the multiple-operator system versus single-operator power sources. This would include all equipment and wiring. The operating cost of the multiple-operator system versus individual power sources must also be considered or assured as equal. Based on the normal lifetime of the equipment, the multiple-operator system will often be the least expensive.

10-8 SELECTING AND SPECIFYING A POWER SOURCE

So far in this chapter the various welding power sources have been described and classified according to the output characteristics of the machine, the current type produced, whether it is rotating or static, and so on. From another point of view, if we know the kind of welding work to be done, it becomes a matter of study to determine the type of welding power source that should be used. The following information provides the data needed to make the most intelligent selection.

1. *Process selection.* This precedes all other factors since it is based on the work to be done. This will generally determine the output characteristics of the power source required.
2. *Welding current.* Most arc welding processes utilize direct current; however, some may utilize either direct or alternating current. When the option is available, the reason for selecting one or the other may depend on the material being welded. This is particularly true for gas tungsten arc welding. For shielded metal arc welding it might be determined by the type of covered electrodes available for the work.
3. *Machine rating.* This is a way of determining the size or capacity of the arc welding power sources. Most welding machines are rated by output current in amperes. Larger electrode sizes require more current but larger electrodes can be used only on heavier work. The size is given in amperes but at a rated voltage.
4. *Duty cycle.* The duty cycle is also a measure of the amount of work that the power source can do. A low-duty-cycle machine does not have the work capacity of a high-duty-cycle machine. Duty cycles range from 20 to 100% and are broken into three classes according to NEMA. The low-duty-cycle class has the least capabilities and therefore is used for intermittent repair work or for the hobbyist. The high-duty-cycle class will be used for heavy-duty industrial applications and for automatic welding.
5. *Availability of power.* This relates to location and whether electric power is available from the utility company. On construction sites, where electric power is not available engine-driven equipment is required. Ther are many situations on new construction sites in which power may or may not be available or in which the expense of hooking up the power line is excessive. In these cases, engine-driven equipment is the logical selection. In general, air-cooled engines have lower-duty cycles than do water-cooled engines. Diesel-powered machines are required when gasoline might present a fire hazard, such as on an offshore drill rig.
6. *Auxiliary devices.* Finally, the selection might depend on auxiliary devices and controls, which will make the welder's job easier. This includes high-frequency current for gas tungsten arc welding or remote capabilities for current control. Auxiliary devices include other items, such as gas and water controls for processes needing them and timers and programmers for critical work.

Each of the preceding factors should be analyzed. In addition, consider the need of flexibility since a power source is a long-term investment and will normally outlast the current job. Will the next job be similar, or will it require more power, or should it have additional capabilities? Many times it is wise to select a machine with a higher current rating so that it will not operate at maximum output for the present job but will have reserve power for other jobs requiring higher currents. Also consider auxiliary devices or features that might be used for other jobs. However, as more features and greater output are required, the cost of the equipment increases. It then becomes a matter of a trade-off between the amount of money to be spent versus the extra flexibility that is desired.

In analyzing these six factors, it is wise to investigate newer equipment since they may include features that would be desirable for the current work. It is also desirable to review the welding procedures to determine current levels and duty cycles needed. With this information

establish the specification for the equipment to be procured.

Specifying the Equipment

To specify a welding power source properly, the following data should be provided.

1. *Manufacturer's type designation.* This can be determined by consulting the manufacturer's catalog or data sheets once the other specifications are known.
2. *Manufacturer's identification number.* This also should be determined from the manufacturer's literature and is usually given as a model number.
3. *Rated load voltage.* Most welding machines manufactured in North America are rated in accordance with the NEMA system. In this system minimum load volts are related to the ampere output of the machine. The 200-A machine has a minimum load of 28 V and this increases as the machine ratings are increased.
4. *Rated load amperes.* Rated current is the current that the power source will deliver at the rated volts. This should be related to the welding procedure requirements.
5. *Duty cycle.* This is the duty cycle at the rated load that the machine will handle. This is given in percent but may be given in conjunction with the NEMA class designation.
6. *Voltage of incoming power.* This is particularly important so that the machine will match your power line. Various input voltages are available to match the power available in all parts of the world.
7. *Frequency of incoming power.* This is the frequency of the power provided by the power company in hertz. In North America this is normally 60 Hz. In other parts of the world it can be 25, 50, or 60 Hz.
8. *Number of phases of incoming power.* Normally, the incoming power is either single-phase or three-phase. Single-phase power is used for limited-input or low-duty-cycle machines. Most industrial equipment utilizes three-phase power.

In the case of engine-driven equipment, it is necessary to specify the maximum rated speed in revolutions per minute at no load.

With this information you can accurately specify a welding power source and be sure of obtaining exactly what is required. Flexibility might again be involved if the machines are to be moved. For example, incoming voltage can be specified with two voltages, such as 230 and 460 V, which will provide flexibility.

10-9 INSTALLATION AND MAINTENANCE OF POWER SOURCES

The installation, maintenance, and adjustment of welding machines and equipment are usually done by different people. In many plants the original installation may be done by construction people, riggers, and electricians. Once the equipment is operating properly they have completed their work. Maintenance is an ongoing operation and is usually done by plant maintenance electricians. Minor adjustments of a routine nature, such as changing tips, nozzles, tungsten electrodes, drive rolls, blowing out cables, and so on, are done by welders. In small shops one person may perform all these operations.

Installation

Installation of welding equipment must be in accordance with the manufacturer's instructions, the company's own standard practices, and all local, state, and national regulations. The manufacturer of welding machines provides information showing the proper method for installing equipment. This usually includes recommended location of the equipment, which should always be in a dry, well-ventilated area, free of excessive dust, moisture, fumes, spray, and so on. Information is given about installing primary power to the welding machine, including the wire sizes, the size of the disconnect switch, and the fuse sizes. Most welding machines are manufactured so that different incoming voltages can be used. The voltage is changed by moving links between studs to properly connect the input voltage to match the power incoming voltage. A wiring diagram showing this information is usually posted on the inside of the welding machine. Various safety rules, such as the *National Electrical Code,* ® the Welding Society's Safety and Health Book, and the requirements of the Federal Safety and Health Administration, must be met. This means that disconnect and fuses of the correct size are required and that the case of the welding machine must be grounded to earth. For gas tungsten arc welding equipment, special installation requirements must be followed to avoid the radiation of high-frequency current from the spark gap oscillator. This involves extra-special grounding to earth of the case and fixtures. This information must be followed explicitly. Other machines may require the installation of gas supply and cooling water supply and drain.

The installation of welding equipment must be inspected with a checklist utilizing the items mentioned above to make sure that it is in accordance with all standards and codes. Motor generator welding machines must be checked for the current direction of rotation at the time of each installation. Rotation is easily checked

since all machines carry an arrow showing the direction of rotation of the armature.

Transformer welding machines must be installed with care. They must be balanced on the three-phase of the power lines and must be phased with respect to adjacent units.

Preventive Maintenance

Preventive maintenance is the routine maintenance performed on equipment while in service so that it does not deteriorate rapidly and fail. This applies to all types of machinery, including welding machines. Preventive maintenance for the different types of welding machines is similar; however, specific types do require specialized attention.

All welding machines and, in fact, all electrical machinery should be kept clean. Dirt and dust from the factory or from the construction site are carried by the ventilating air through the welding machines. This dirt collects in the internal parts of the welding machine and tends to build up on windings and prevent them from cooling efficiently. The dirt may also build up to the point where it blocks the passage of cooling air through the machine. Welding machines should be inspected every six months and cleaned. In an extra-dirty environment with excessive amounts of dust, dirt, lint, or corrosive fumes, the inspection period should be shortened. Filters can be installed on the machine when required.

The welding machine should be cleaned by qualified personnel. For safety reasons, the power should always be disconnected at the wall switch so that live power leads are not inside the welding machine case. The dirt should be removed from the windings by blowing them out with clean, dry compressed air at a pressure of 25 to 30 psi. All foreign material should be removed. High-pressure air should not be used since this will tend to drive the dust and dirt into crevices which will reduce the cooling efficiency of the machine. Vacuum cleaning can be used, particularly if metallic dust is present inside the case. In very dirty environments, filters are recommended to keep dust from entering the machine.

At this inspection be alert for dirt on switch contact points, and check for loose internal and external connections. For machines with cooling fans make sure that the fans are operating and that the fan motors are clean. Look for internal corrosion, internal mechanical damage, and external damage of any type.

Engine-Driven Generators The normal engine maintenance should be performed on the engines of welding machines. Change oil after every week of continuous operation. This may need to be done more often in especially dirty locations. Inspect and replace, if necessary, oil filters, air filters, and fuel filters. Check coolant and batteries each time fuel is added. The linkage and idling devices should be checked weekly. The radiator should be checked daily to make sure it is full of coolant and free of obstructions. The engine manufacturer's recommendations should be followed.

Generators Generators should be checked monthly. This includes the windings, contact points, the brushes and brushholders, the commutators, the controls, and the bearings. The brushes should be inspected to make certain that they are bearing properly on the commutator. This applies to the exciter as well as to the main generator. Check also to make sure that the brushes have not worn too short and if so, new brushes of the same grade should be used for replacement. The pigtail to the brush should be checked and tightened to the connection. The brushes should move freely in the brushholders but should be held against the commutator by the springs. Broken or weak springs should be replaced. The commutator should also be checked for dirt and discoloration. If it is burned or excessively rough, it should be removed and turned on a lathe. For minor discoloration, it can be cleaned with fine sandpaper. Emory paper or cloth should not be used since the dust is conductive and will tend to short out adjacent bars. New brushes should be sanded to make sure they are in full contact with the commutator.

Bearings should be checked monthly: sealed bearings do not normally need grease. However, when grease is required, the bearings should be thoroughly cleaned of all old grease and new grease should be installed. Bearings should not be filled full with grease, but should leave sufficient space for the grease to move. All electrical connections should be checked for tightness and all contacts, starters, switches, rheostats, and so on, should be inspected and cleaned as required. If the machine is exposed to corrosive or salt atmospheres, special attention should be given to exposed metallic parts. If corrosion is found, the part should be cleaned and repainted and insulation should be replaced.

Static Machines The nonrotating machines usually include a fan. The fan motor should be checked as well as the bearings to make sure that the fan operates freely. All the foregoing instructions, with respect to contact points, moving switches, or rheostats should be followed. Check for corrosion and repair as required. On machines with mechanical current adjustments and moving cores and coils, the lead screws and guides should be greased for ease of adjustment. Where conductors flex within the machine, they should be checked for insulation damage and replaced as required.

On gas tungsten arc welding power sources, special attention should be given to the spark gap oscillator. The spark gap should be adjusted with a spacing of from 0.006 to 0.008 in. (0.15 to 0.2 mm). The contact faces should be cleaned, and if they are pitted, they should be re-

dressed. The gas and water valves should be checked to make sure that they are operating and that there are no leaks in either the gas or cooling water system. Timers and programmers should be checked for calibration and adjusted as required. Solid-state circuit boards should be clean and secured in place. Relays and other contact points in control circuits should be checked for proper closing and opening and points dressed if required.

It is advisable to keep a detailed inspection record for each machine by serial number, by inspection and periodic maintenance date, and by extra activities or maintenance that was required. This will help determine if specific machines require extraordinary attention.

Troubleshooting

Troubleshooting is required on a welding machine when it is not operating satisfactorily. It is assumed that the machine had been properly installed and was operating satisfactorily before the problem occurred. Troubleshooting is a matter of solving the problem of the machine and should be done only by qualified personnel. There are two types of troubleshooting. One is a method of diagnosing the problem while the machine is in operation or is energized. This type of work should be done with the case of the machine intact. The other type of troubleshooting is done with the machine completely deenergized and working on the inside of the equipment. Electrical meters can be used in either case.

Figure 10-54 will cover many of the problems that may be encountered with most arc welding machines.

The 15 factors above cover the more general problems that can be corrected by routine troubleshooting while the equipment is in service.

It is sometimes difficult to distinguish between a *welding problem* and a *welding equipment problem*. This is particularly apparent when the welder is utilizing unfamiliar equipment or when first using a different welding process. Each of the welding processes have their own specific problem areas and many times the welder may tend to blame the problem on the equipment when it might be a problem with the process. An example of this might be a poor weld due to the lack of shielding gas when using the gas tungsten arc process. The lack of shielding gas can result from a malfunction of the machine such as a solenoid valve, or it could result from an empty gas cylinder, a stray breeze, a clogged hose, or a loose connection in the torch. It is wise to review each of the welding process chapters when troubleshooting equipment used for that welding process. Difficulties can also be encountered when the equipment is not properly adjusted. A very rough arc, for example, when welding with gas metal arc welding using a small electrode can be the result of an out-of-balance adjustment between the welding current and voltage. The equipment might be blamed but it is really a problem of maladjustment. Skillful diagnosis is required to determine the true cause of a welding problem.

Figure 10-55 is provided for welding equipment with specific emphasis on particular welding processes. This information plus a working knowledge of the processes will assist in troubleshooting a problem and making a quick and accurate diagnosis.

If the high-frequency current does not start:

1. Make certain that proper line voltage is at the machine and that no fuses are blown or circuit breakers tripped.
2. Make certain power switch is on and fan is running.
3. Check reset button on machine overload trip.
4. Rectifier thermostat may have tripped. Wait 5 minutes with fan running and reset.
5. High-frequency switch may be in the wrong position.
6. Check the remote–local switch to make sure that it is in the proper position.
7. Make certain that the torch is connected to the "GTAW or TIG torch" terminal and that the work lead is securely connected to the *work* terminal and to the workpiece.
8. Check the spark gaps. They should be set between 0.006 and 0.008 in. (0.15 and 0.2 mm).
9. Check for broken high-voltage leads in the spark gap oscillator circuit. Also check components of the circuit.
10. Check for 230 V to the spark gap oscillator. Use *caution*—line voltage is present at various terminals.

If the high-frequency circuit is weak:

1. Check tightness of all leads in the external welding circuit.
2. Increase high-frequency rheostat to maximum.
3. Maximum recommended welding cable length is exceeded. Have the machine as close to work as possible.
4. Welding cables should lie in a straight line from the machine to the work for maximum high frequency. Avoid having work and electrode cables touch each other and avoid having them in contact with metallic objects or lying on metal.
5. Check spark gaps—adjust if required.
6. Make certain that the shielding gas is flowing.
7. If the checks above are of no help, run checks listed under "If the high-frequency current does not start."

Problem	Cause	Remedy
1. Machine will not start (equipped with or without line contactor)	Power lines dead	Check voltage
	Broken power lead	Repair lead
	Incorrect line voltage	Check power supply
	Incorrect connections to welding machine	Check connections against connection diagram
	Blown fuse	Replace fuse
2. Machine will not start (equipped with line contactor only)	Overload relay tripped	Reset relay
	Open circuit to starter button	Repair
	Mechanical obstruction on starter	Remove obstruction
	Broken leads at line contactor	Repair
3. Line contactor chatters during welding operation	Input cable too small	Install larger cable
	Low line voltage	Check incoming power
4. Contactor hums	Dirt on contacting faces of line switch magnet	Clean faces of magnet
	Improper alignment of stationary and movable yokes on starter	Correct alignment
5. Contactor operates and blows fuse	Wrong line voltage	Check line voltage and nameplate of welding machine
	Links on line contactor not connected correctly	Check and correct
	Fuse too small	Install proper-size fuse
	Rectifiers burned out (rectifier and ac–dc machines only)	Replace rectifier
	Short circuit in primary connections	Remove short circuit
	Transformer failure	Repair transformer
6. Welding machine delivers welding current but soon shuts down	Wrong overload relay elements	Check with renewal part recommendation
	Welding machine overloaded	Overload can be carried only for a short time; reduce welding current
	Duty cycle too high	Do not operate continually at overload currents or reduce welding current
	Power leads too long or small	Replace with larger cable
	Ambient temperature too high	Operate at reduced loads where temperature exceeds 100°F (37.8°C)
	Ventilation blocked	Check air inlet and exhaust openings
	Fan not operating (fan-cooled machine only)	Disconnect leads and apply motor voltage to check nameplate voltage
	Dirty rectifiers (rectifier and ac–dc machines only)	Clean with low pressure air blast—do not use wire brush or abrasives
7. Contactor operates but welding machine will not produce welding current	Welding terminal shorted	Electrode holder or cable may be shorted

FIGURE 10-54 Troubleshooting chart for arc welding power source.

Problem	Cause	Remedy
7. *(cont.)*		
Contractor operates but welding machine will not produce welding current	Range switch or polarity switch not centered on arrow or detent.	Set to arrow or detent
	Transformer lead open	Have transformer repaired
	Transformer secondary failed	Have transformer repaired
	Rectifier burned out (rectifier and ac–dc machines only)	Replace rectifier
8. Welding arc is loud and spatters excessively	Current setting too high	Check setting and output with ammeter, or reduce current
	Polarity incorrect	Check polarity, try reversing polarity
	Incorrect electrode used on ac	Use ac or ac–dc electrode for ac welding
	Filter coil short circuited (ac–dc machines)	Replace filter coil
9. Welding arc sluggish	Current too low	Check output, and current recommended for electrode being used
	Poor connections	Check all electrode holders, leads, and work lead connections
	Cables too long or too short	Check cable voltage drop; change cable
	Low line voltage	Check incoming power; notify power company, if necessary
	Power circuit single phased (on three-phase rectifier machines)	Check for one dead line or fuse
10. Control knob does not control welding current	Rheostat burned out	Replace
	Control rectifier burned out	Replace
	Loose connection in control circuit	Check connections at control rectifier and control coil
	Control coil failed	Have transformer repaired
11. Range switch or selector does not control welding current	Dial or moving contacts slipping on shaft	Replace dial or moving contact; tighten on shaft; clean switch and grease
12. Polarity switch does not control polarity	Dial or moving contacts slipping on shaft	Replace dial or moving contacts; tighten on shaft; clean switch and grease
13. Welding machine operates, but welding current falls off	Electrode or work lead connections loose	Clean and tighten all connections in welding circuit
14. Receive shock when machine case is touched	Case of machine not grounded	Ground case to earth
15. Shock when work lead, work, or worktable is touched	Worktable and work not grounded	Ground work and worktable to plant ground

FIGURE 10-54 *(cont.)*

Problem	Cause	Remedy
1. When using the GTAW process on ac the weld metal *curdles*, and the arc is violent	Arc is played on weld puddle	Point torch in direction in which you are welding, not directly into the weld puddle
	Current too high	Reduce current
	Arc length too long	Hold closer arc
	Contaminated tungsten electrode	Redress the tungsten electrode
	Gas nozzle on torch too small	Increase size of gas nozzle
	Too little or too much gas flow	Adjust gas flow according to procedure
	High frequency too weak	Check high frequency as outlined below
	High frequency rheostat not set properly	Adjust for best welding conditions
	Wrong spark gap setting	Adjust spark gap as recommended
	Impure inert gas	Change gas cylinders
2. Torch spits tungsten into the weld	Arc length too long	Hold closer arc
	Tungsten too small	Use larger size tungsten electrode
	Current too high	Decrease current
	Pure tungsten electrodes used at very high currents on ac	Use thoriated tungsten
3. The weld is dirty	Dirty base metal	Clean the base metal
	Dirty filler rod	Keep filler rod clean
	High frequency set improperly	Adjust high-frequency rheostat for optimum operating conditions
	High frequency too weak	Increase setting of high-frequency rheostat
	Too little or too much gas flow	Adjust gas flow according to procedure
4. On DCEN the high-frequency jumps the arc gap, but dc power does not follow to initiate the arc	Use of pure tungsten electrode	Use thoriated tungsten for dc electrode negative
	Use of helium gas	Use argon gas for better arc initiation
	Tungsten electrode too large	Use smaller tungsten or grind to a point
5. Arc wanders	Tungsten too large	Use smaller tungsten
	Tungsten contaminated	Redress tungsten electrode
	Arc blow	Change position of work lead clamp
6. Tungsten turns purple after weld	Insufficient gas postflow	Increase setting of postflow timer
	Postflow timer sticks	Replace
	Gas valve sticks	Replace
7. Water to torch flows too slowly or not at all	Insufficient water pressure	Increase pressure
	Water strainer in circulation system is clogged	Remove and clean or replace
	Water valve sticks	Replace
8. Water or gas does not shut off	Postflow timer set too high	Decrease postflow timer setting
	Postflow timer contacts stick	Replace timer
	Valves stuck open	Replace valves

FIGURE 10-55
Troubleshooting chart for GTAW power source.

Additional items can be added to your own checklist depending on the complexity of the equipment being used.

This checklist can be modified and used for gas metal arc welding, but all reference to high frequency should be eliminated. See manufacturer's instruction book.

Repairing

If the diagnosis indicates that the machine must be repaired, it should be removed from service and taken to the maintenance repair shop. If in-house facilities are not available, the equipment should be sent to an authorized repair station. These are usually local electric repair shops that have been approved by the manufacturer of the welding equipment. It is essential that genuine replacement parts are used for all repair work and that the repair mechanics have sufficient knowledge and skill to accomplish this work. After the machine has been repaired it should be tested and checked to make sure that it will fulfill its original function.

QUESTIONS

10-1. There are six ways of classifying a power source. Name each and explain.

10-2. Discuss NEMA classes I, II, and III—how is duty cycle described?

10-3. What are the static characteristics and dynamic characteristics of a power source?

10-4. How can you determine the 100% duty cycle rating of a 60% machine? Explain.

10-5. What is the difference between a static and a rotating exciter?

10-6. How is the polarity of a generator welding machine changed?

10-7. What are the principal methods of adjusting the output of a transformer welding machine?

10-8. How does the saturable reactor system work?

10-9. What determines the output open-circuit voltage of the transformer power supply?

10-10. What are the disadvantages of a transformer welding machine?

10-11. What is the function of the rectifier?

10-12. Why can the rectifier power source be connected to three-phase power?

10-13. What is a combination ac–dc welding machine? What is its advantage?

10-14. What is the advantage of an inverter-type power source?

10-15. In a multioperator system, what is load diversity?

10-16. Can welding be done simultaneously with DCEP and DCEN using a multioperator system?

10-17. Why does the multioperator system provide a smooth arc?

10-18. What data are necessary to specify a welding power source?

10-19. Who should do electrical troubleshooting on an electrically hot power source?

10-20. What is preventive maintenance? How does it apply to welding machines?

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11

Other Welding Equipment

11-1 ARC WELDING GUNS AND TORCHES

All of the arc welding processes use a special device to transmit the welding current from the welding cable to the electrode. These come in many different types and sizes and are given different names. In shielded metal arc and carbon arc welding the device is called an electrode holder. They are designed to hold short lengths of electrodes. Electrode holders are described in the sections on shielded metal arc welding and carbon arc welding.

For gas tungsten arc welding the device is called a welding torch or gun. It holds the tungsten electrode and transfers the welding current to it. It is described in the section on gas tungsten arc welding. The torch or gun for plasma arc welding is similar but contains an orifice that develops the plasma. Plasma arc torches are described in the section on plasma arc welding. Stud welding uses a special gun which involves mechanical action to carry out the stud welding operation. Stud guns are described in the section on stud arc welding.

There are no specifications in the United States for welding electrode holders, torches, or guns. In view of this, manufacturer's data are consulted in order to specify the electrode holder, gun, or torch required.

The guns or torches for gas metal arc welding and

OUTLINE

flux-cored arc welding are used to direct the welding electrode into the arc, to transmit the welding current to the electrode, to supply shielding of the arc from the atmosphere, and to perform other duties. In general, they are called guns when used for semiautomatic applications since they are hand-held. They are called torches when used for mechanized welding. Welding guns and torches are categorized according to the welding process or process variation employed.

The guns for semiautomatic submerged arc welding are different from the guns for the gas-shielded processes, because it also feeds the submerged arc flux. There are two systems. In the first method, small amounts of flux are carried in a hopper attached to the gun (Figure 11-1). The second method utilizes a compressed air pressure system to feed the flux through the cable assembly to the gun (Figure 11-2). The cable assemblies attached to the guns are available in different lengths. Extended-stickout tips are available for some guns for submerged arc welding.

A major function of the torch or gun is to deliver the welding current to the moving electrode wire. This is done by means of a contact tip or contact jaws. The amount of current transmitted is a way of sizing welding guns and torches. This is the welding current rating, normally the maximum current that can be used with a particular gun or torch. Higher currents usually involve larger-diameter electrode wire. Sliding contacts for transmitting large amounts of current will generate heat. Heating of the gun occurs from this as well as from its closeness to the welding arc. This points out another way of classifying guns and torches—the method of cooling, which is by means of circulating water or ambient air.

FIGURE 11-1 Hopper feed semi-automatic gun for SAW.

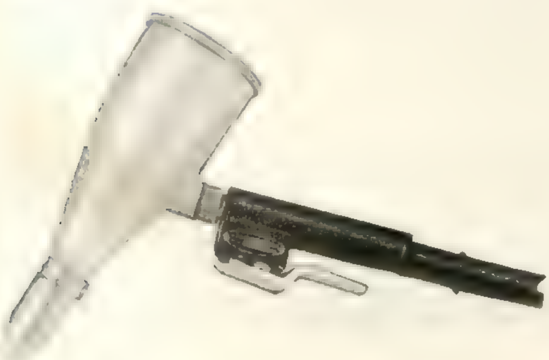
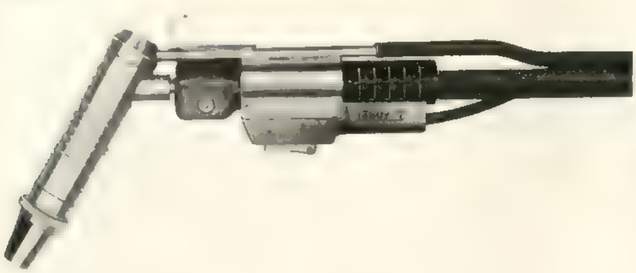


FIGURE 11-2 Pressure feed semi-automatic gun for SAW.



Another function of the gun or torch is to deliver shielding gas to the arc area. Shielding gas is not used with variations of flux-cored arc welding; hence there are gas-shielded and non-gas-shielded types of welding guns and torches. They are called gas-shielded or gasless guns.

Another way of classifying guns is by their shape, which relates to welding wire type and welding position, but also to the preference of the welder. The two most common are the curved head or gooseneck configuration, and the straight-line pistol-grip variation. Automatic torches can also be either straight-line or bent with different angles for specific applications.

The hand-held semiautomatic guns normally employ a trigger which activates the control circuit. Electrode touch starting is sometimes employed but is becoming less popular. With a trigger switch, the voltage of the circuit must be supplied from an isolated voltage source and must not exceed 35 V ac or 50 V dc. This is a provision of the NEMA standards.[1] The NEMA standard also identifies maximum temperatures on external surfaces of welding guns. The maximum temperature of a metal handle is 140 °F (60 °C), or if the handle is nonmetallic the maximum temperature can be 185 °F (85 °C). The maximum temperature of the nozzle is 158 °F (70 °C) if metallic; if nonmetallic it can be as high as 203 °F (95 °C). The maximum temperatures are based on continuous use.

Welding Guns

The welding guns can be categorized as curved head or gooseneck and straight-line or pistol-grip guns. They are further subdivided into air-cooled or water-cooled guns. For flux-cored arc welding they can be subdivided into those using external gas shielding and those using self-shielding electrodes. A typical straight-line and curved head welding gun is shown in Figure 11-3. A cross-sectional view of the curved head or gooseneck gun is shown in Figure 11-4. A pistol-grip water-cooled straight-line gun is shown in Figure 11-5. The gasless gun, for flux-cored arc welding, is shown in Figure 11-6. This also shows the details of the contact tube or tip for electrical stickout. This is often required since the self-shielding flux-cored electrode wires normally operate more efficiently with extended stickout.

For low-current gas metal arc welding the gooseneck-type air-cooled guns are usually employed. When CO_2 shielding is used, with larger-diameter electrodes at higher currents, an air-cooled gun can be used since the CO_2 is a cooling medium. When inert gas or argon-oxygen gas mixtures are used at higher currents, the guns

FIGURE 11-3 Curved- and straight-line welding guns.

must be water cooled to avoid overheating.

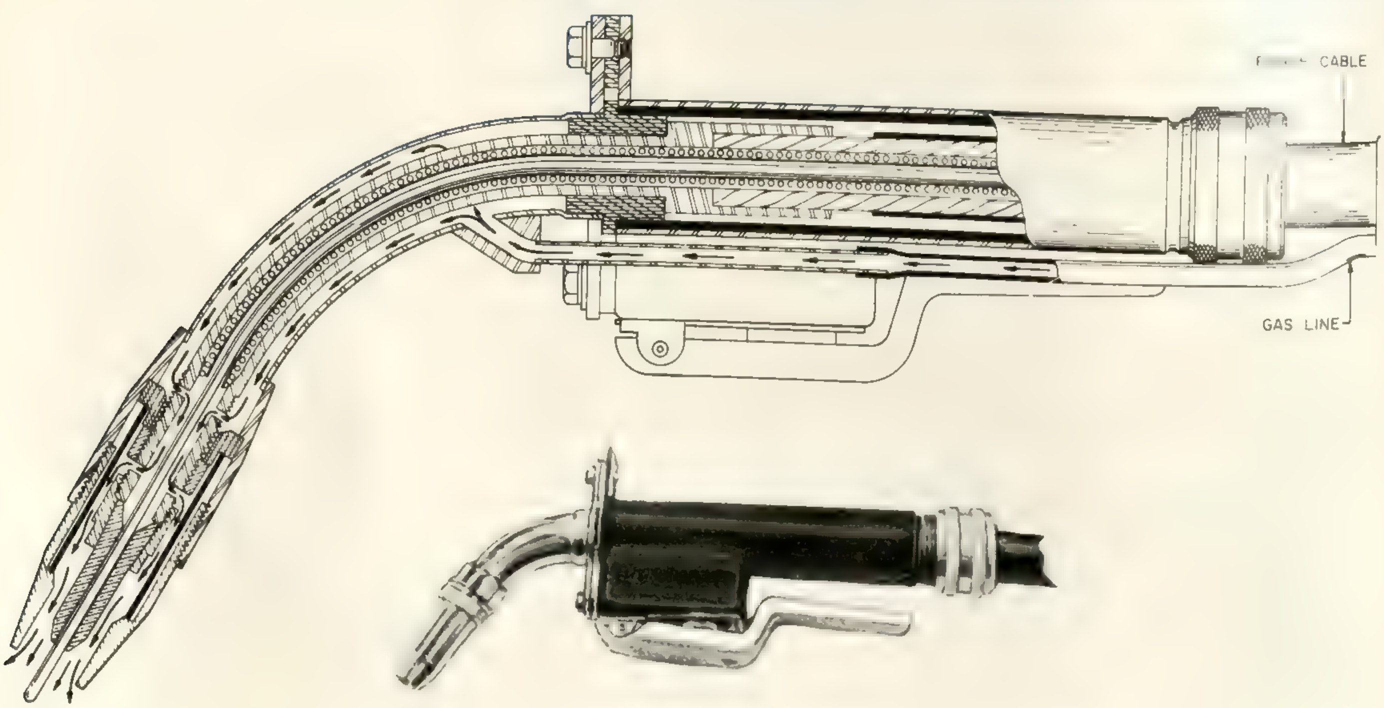
Hand-held semiautomatic guns include the cable assembly, which attaches to the wire feeder. Cable assemblies are available in different lengths. The cable assembly includes the conduit tube for the electrode wire, a tube for supplying shielding gas, and two tubes for cooling water when used, plus the control cables to the trigger switch. It also includes the electrical conductor for the welding current. The size of this conductor is related to the rating of the welding gun. The welding guns allow the use of different nozzles and the replacement of the contact tube or tip.

The gun nozzle is usually identified by the inside diameter at the shielding gas discharge end. They are different for each manufacturer and may fit only the guns of the same make.

The welding guns have replaceable contact tips or tubes for transferring current and guiding the electrode wire to the arc. These come with different inside diameters to accommodate different-diameter electrode wires. Manufacturers recommend specific tips for specific wire types and sizes. Efficient transfer of current from the cable to the electrode wire is necessary to avoid overheating. Contact tips are made of copper or copper alloys. Pure copper is very soft and the inside diameter will wear rapidly. When the inside hole becomes oversized the welding current transfer efficiency diminishes and more heat will be generated. Hence contact tips must be changed on a regular basis. Long-wearing contact tips are available and are made of special copper alloys. In some cases, special inserts are incorporated. The copper alloys are much harder than pure copper and will provide much longer life but are more expensive.

For welding aluminum, extra-long contact tubes are recommended because of the oxide coating on the aluminum electrode wire. The extra-long contact tubes provide more area to transfer the welding current to the electrode wire. To improve the current transfer, some contact tubes incorporate a slight bend to make sure that there is positive sliding contact between the electrode wire

FIGURE 11-4 Goosenecked gun for GMAW and FCAW.



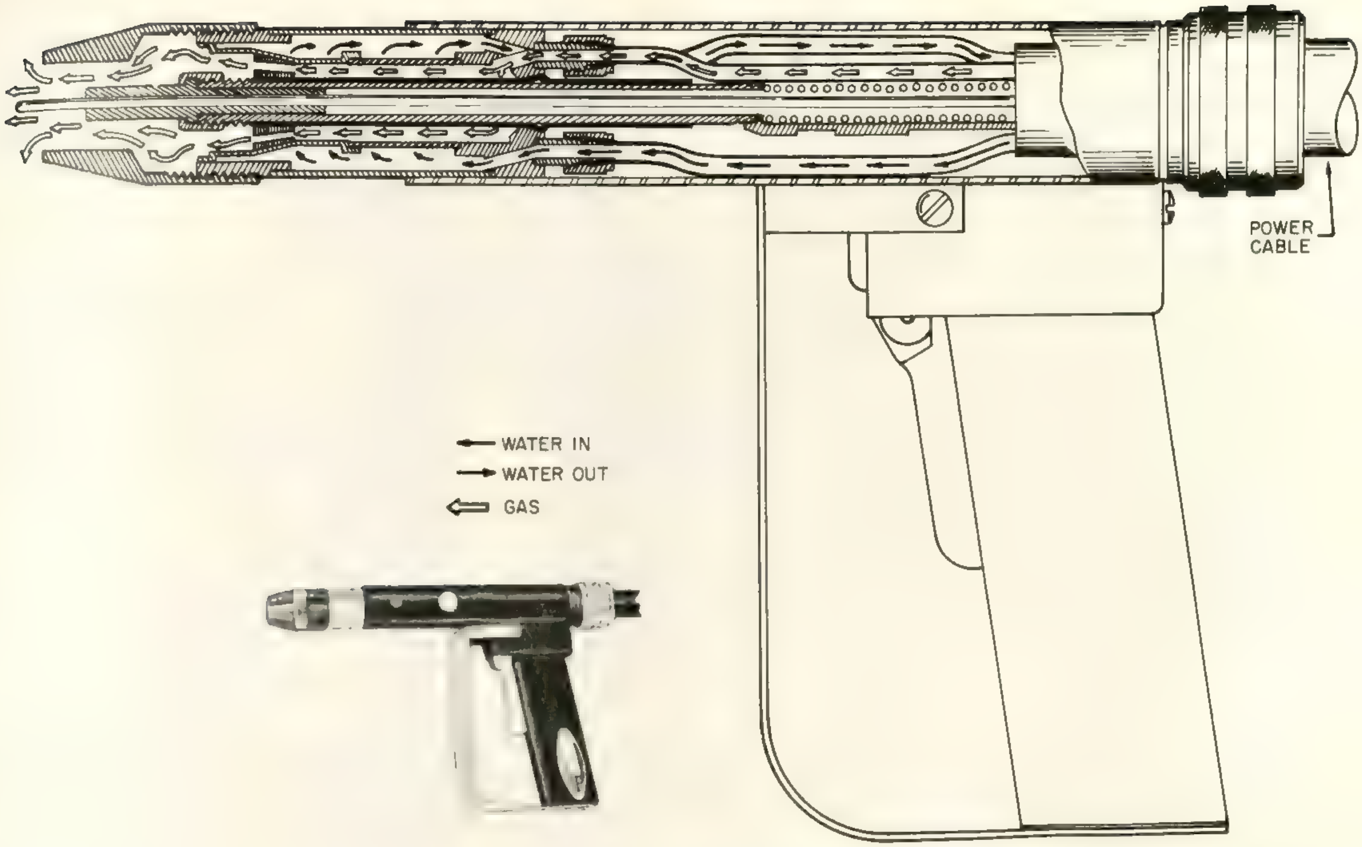
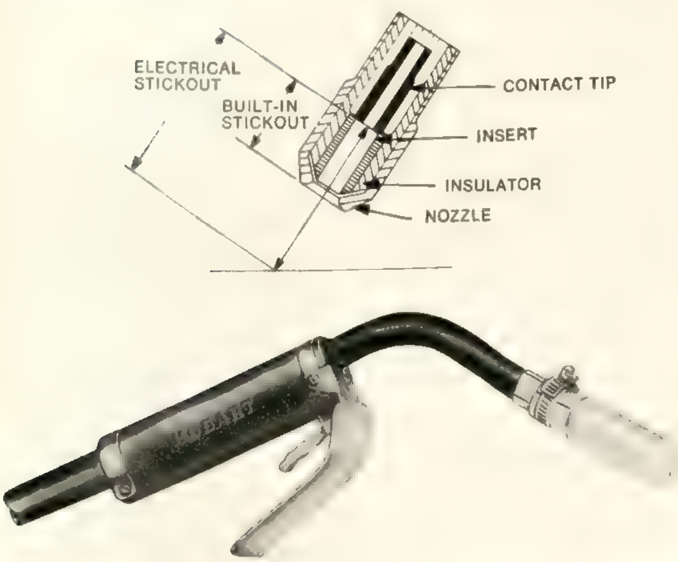


FIGURE 11-5 Pistol grip–straight-line gun, water cooled.

and the contact tip. Longer contact tubes usually mean straight-line pistol-grip guns. Additionally, gooseneck guns are less desirable for feeding soft-aluminum electrode wires because of the bend.

There is no standard method of rating welding guns or torches or for measuring the angle of goosenecks, the weight or balance point, or the size of the guns. In view of this, it is necessary to use manufacturers' data to specify guns and torches. Most manufacturers provide a duty cycle rating for use with CO_2 shielding gas and for inert shielding gases.

FIGURE 11-6 Gasless gun for FCAW, showing nozzle detail.



The gooseneck type of air-cooled gun is most popular for welding steels, particularly using small-diameter electrode wire. The pistol-grip or straight-line gun is more often used with aluminum since the curve in the gooseneck gun tends to create resistance to the electrode wire, which may cause jamming the cable assembly.

Welding guns and cable assemblies must be maintained regularly in order to provide efficient operation. The filler wire conduit must be replaced on a regular basis since it tends to fill with loose copper coating, metal shavings, and so on.

Adapters are available for attaching the gun cable assemblies of one manufacturer to the wire feeder of another. Quick-connection adapters are also available and widely used.

Automatic Welding Torches

Torches for mechanized welding are usually straight-line torches. Figure 11-7 shows a variety of torches for specific applications. The two torches on the left are used for smaller-diameter electrode wires and in fixtures where space is at a premium. The torch on the extreme left provides concentric shielding gas delivery and the next one

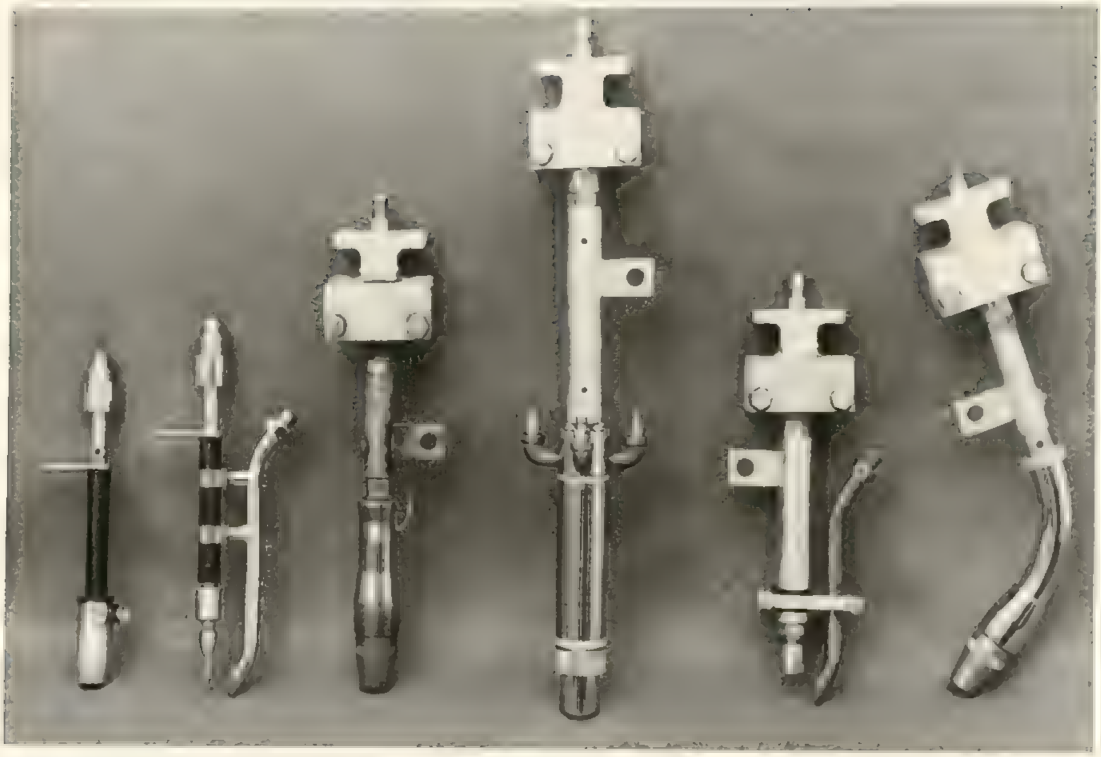


FIGURE 11-7 Torches for automatic welding.

is for side delivery of CO_2 shielding gas since CO_2 gas is used at a higher flow rate. Side-delivery systems normally pick up less spatter and are widely used for automatic systems. Side-delivery torches should be used only when CO_2 is used for shielding. The other four torches are for larger-diameter electrode wires. The third and fourth torches are for concentric gas delivery. The larger one is water cooled and can be used for inert shielding gas. The fifth torch utilizes larger electrode wire and has the side delivery of CO_2 shielding gas. This same torch is used, without the side-delivery nozzle, for submerged arc welding and for gasless flux cored arc welding. There are exceptions to the straight-line design, shown by the extreme right-hand torch. This is curved for a specific automatic application. This type of torch is also used for robotic arc welding.

The automatic torch must be selected to accommodate the welding procedure and welding process. The torch must be selected with respect to the size of the electrode wire and the current range and duty cycle of the operation. Most torches are rated by current-carrying capacity and electrode size. It is generally best to utilize a torch rated at a higher current level than will be employed. In addition, weight is less important since it is held by the machine rather than by the welder. Torch current pickup tubes or tips can be selected to accommodate different wire sizes. For large electrodes, heavy-duty torches with spring-loaded current contact jaws are used. Spring-loaded contacts usually are made from special hardened copper alloys. The jaws are loaded against the wire to provide efficient transmission of the current to the wire for cooler operation.

11-2 ELECTRODE FEED SYSTEMS

All of the continuous electrode wire arc welding processes require an electrode feeder of one type or another. It is used to feed the consumable electrode wire into the arc. A major component of the electrode feeder system is the wire feeder. There are many types of wire feeders. The most widely used is used with the consumable wire processes, where the electrode is part of the arc welding circuit. The other type of feeder, known as a "cold wire" feeder, is used with the arc welding processes, where the electrode is not part of the welding circuit. The basic requirement of the wire feeder is to feed the electrode continuously into the arc and to maintain a stable arc at the desired welding current and voltage. The basic requirement of the cold wire feeder is to feed the filler wire into the arc area at the correct rate to maintain proper melting and deposition. The components of a wire feeding system are the welding gun or torch, the wire drive mechanism, the control circuit, and the wire handling and dispensing system.

Wire Feeder Types

Welders needed semiautomatic equipment that would have the same flexibility and portability as shielded metal

arc welding. Many developments have been made to provide this flexibility. It is now possible to weld almost anywhere and to make almost any kind of joint with semiautomatic equipment. The wire feeder is at the heart of the system and has been developed in many forms.

The most common type of wire feeder used for semiautomatic welding is shown in Figure 11-8. Feeders of this type carry the supply of electrode wire, the wire drive mechanism, the control circuit, and the adjustment for wire feed speed. They are sufficiently powerful to push electrode wires through a long cable assembly using gooseneck welding guns. These feeders usually carry 25-lb spools of electrode wire and have optional accessories such as wire covers, water valves, wheels, and so on.

FIGURE 11-8 Conventional wire feeder.

To provide better portability, smaller, enclosed or suitcase-type wire feeders are available. These weigh slightly over 20 lb and will pass through 14-in.-diameter manholes. They are totally enclosed and normally use a small spool of electrode wire which can carry 20 lb of steel or 5 lb of aluminum electrode wire. A typical example is shown in Figure 11-9.

Ultimate portability is attained by the combination wire feeder and gun, known as a spool gun. The wire feed motor is located in the handle, with the drive rolls just behind the gun nozzle. A control box is required, which can be located at the welding station or at the welding power source. Spool guns are popular for welding aluminum. The spool of aluminum wire normally weighs 1 lb. These guns are well balanced for ease of manipulation, but are more awkward to use than gooseneck guns.

FIGURE 11-9 Portable wire feeder.

The disadvantage of spool guns is that filler metal is more expensive when purchased on small spools, and the life of the drive motor is shorter than of heavy duty feeders. A typical spool gun is shown in Figure 11-10.

In some cases the wire feeder is built into the power source cabinet. This provides a single unit which is relatively portable. This kind of equipment can be taken into remote areas. It is also used for light production work and by hobbyists, and normally operates on 115 V ac. A typical example is shown in Figure 11-11.

When different welding parameters are used on the same job, several different types and sizes of electrode wires will be required. An example is the root-pass welding of a pipe joint with the filler passes made by larger-diameter flux-cored wire. For this kind of work a dual wire feeder is used, with two different coils of electrode

FIGURE 11-10 Spool gun for GMAW.

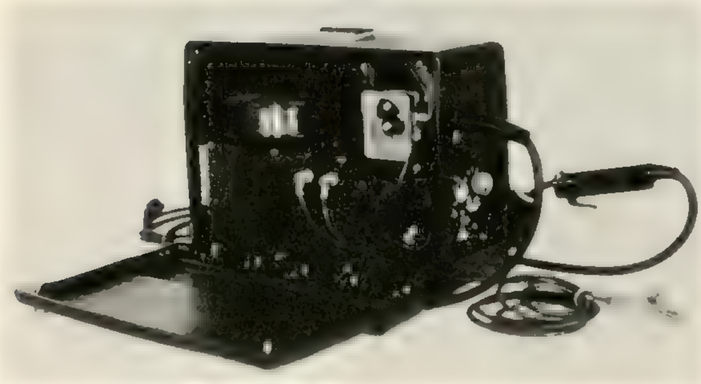


FIGURE 11-11 Combination power source and wire feeder.

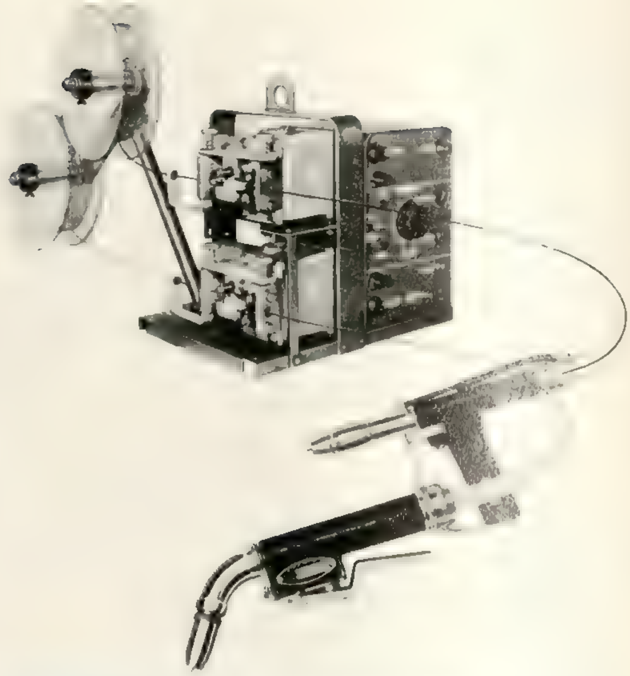


FIGURE 11-12 Dual-electrode wire feeder.

wire and two gun–cable assemblies. Units of this type are very common in pipe fabrication shops. A typical example of a dual wire feeder is shown in Figure 11-12.

Another example of portability is the planetary-type wire feed system. In this case a drive head is located in the welding gun, booster feeders are placed in the cable, and a feeder is at the wire supply. An example is shown in Figure 11-13, which shows that the welding gun can be many feet from the power source.

Equipment with flexibility that uses large packages of filler metal is the push-pull systems. A drive motor included in the welding gun pulls the electrode wire, and another drive head placed at the wire supply pushes the electrode wire. These motors are designed so that the pull unit maintains a very slight tension on the wire as it passes through the flexible conduit and prevents kinking of the wire. These units are used for aluminum welding.

The cold wire feeder is an entirely different type of wire feeder, used to feed filler metal into the arc. It is used for gas tungsten, plasma arc welding, and for the high-energy beam welding processes. It is also used for a few applications with submerged arc welding. Normally, the filler metal does not carry current. An exception is a variation known as "hot wire" welding, where the filler wire carries current to improve deposition rates. Current and voltage are sufficient to heat the filler wire but not to create a welding arc. The feed rate of the cold wire feeder must be very accurate and the wire feed must have a continuously adjustable speed over a wide range. Cold wire feeders feed wire at a much lower rate than do electrode wire feeders. A typical example of a cold wire feeder for a gas tungsten application is shown in Figure 11-14.

One of the newest types of wire feeder is the electronic control type, which allows presetting the wire feed speed and arc voltage. Some wire feeders have two or more schedules that can be preprogrammed into the controller memory circuit. This allows more control of the welding operation, but also allows the welder to select different schedules for different types of work. A typical example is shown in Figure 11-15.

Special wire feeders are sometimes required for pulsed arc welding and/or synergic welding. These require coordination controls between the wire feeder and the power source, but are easily adjusted by the welder.

There are features that should be incorporated in wire feeders for semiautomatic welding. These include at least the following. The wire feed motor and electrode supply should be insulated from the cabinet so that the wire feeder can be placed on the work. The gun cable assembly must be easily attached and detached from the wire feeder. Certain controls should be at the wire feeder: the inch button to thread a new coil or wire, the

FIGURE 11-13 Welding with linear wire feed system.

inch/reverse switch to retract the wire, and the purge button. The control circuit should include dynamic breaking of the wire to prevent coasting, it should include preflow and postflow of shielding gas, and it should have a burnback control for crater filling.

Control Systems

The control system, or control circuits, are of different types depending on the features required of the wire feeder and the type of power source involved. There are two basic types of systems, dictated by the type of power source involved. The most popular type is the constant feed speed system, which utilizes the fixed burn-off rate versus welding current relationship of the electrode wire. This system must be used with a constant-voltage or "flat" characteristic power source. The electrode wire feed rate is set by the speed control of the wire feed motor. The CV power source automatically furnishes the correct amount of current to burn it off at the same rate that it is fed into the arc. Thus the wire feed rate controls the welding current. The voltage at the arc is controlled by changing the output voltage of the power source. It is a self-regulating system and is popular for small-diameter electrode wires. It was originally developed for gas metal arc welding, to eliminate stubbing and burnback. The wire feed rates of constant-speed wire feeders are adjustable over a wide range of speeds. The range must include the welding conditions involved

FIGURE 11-14 Cold wire feeder.

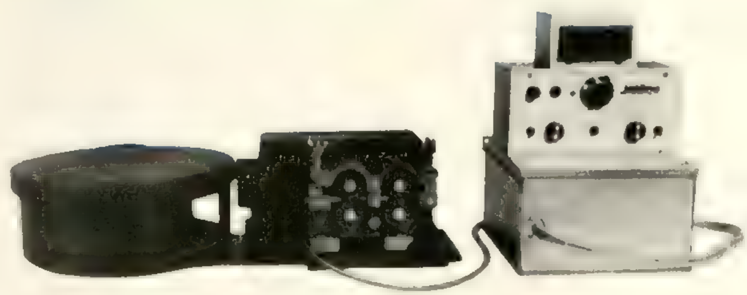


FIGURE 11-15 Wire feeder with electronic memory.

in the desired welding procedure. A constant-speed wire feeder may be used on a CC or "drooping" characteristic power source, but it may be difficult to adjust the various controls properly; furthermore, sudden change in welding conditions may cause the system to go "out of control."

The voltage-sensing wire feeder utilizes the voltage across the arc and regulates the wire feed speed to maintain a preset arc voltage. This type of unit is used with the constant-current "drooping" type of power source. The control system replaces the "feeding" action of the welder. It slows down or speeds up the feed rate of the electrode wire to maintain the set arc voltage. This system uses the arc voltage to control the wire feed motor. As the arc lengthens, the arc voltage increases, which increases the speed of the wire feed motor. This causes the electrode to feed faster and thus shorten the arc. Another system uses a feedback circuit which takes the arc voltage and compares it to a standard, and the difference is used to vary the speed of the wire feed motor. The voltage-sensing system is self-regulating. Welding current is adjusted at the welding power source. A voltage-sensing wire feeder may be used for either dc or ac welding. It is most popular for feeding large-diameter electrode wires and was originally developed for submerged arc welding. The wire feed system may also include a retract circuit for automatically initiating the arc. Touch start and quick break of the arc are used for starting and stopping the arc in many semiautomatic systems; however, a trigger circuit is more popular. A comparison of the electrode wire feeder types and power source types for different applications is shown in Figure 11-16.

The newer control circuits include memories for multiwelding schedules and also provide precision controls for pulsed MIG and GMAW welding, with particular emphasis on synergic systems. These are more complex control circuits which are incorporated into the wire feeder controller.

Wire Drive Mechanisms

The wire drive mechanism, also known as the feedhead, consists of the drive motor, gearbox, and drive rolls assembly that actually feeds the wire. It is used in practically every semiautomatic wire feeder made. For feeding wire the pinch-type drive rolls are by far the most popular, used in over 99% of the wire feeders.

Several other feed systems are now available. Three new types are known as the planetary or linear feeder, the capstan feeder, and the multigrip feeder. The linear concept uses the planetary motion of two or three drive rolls. They are mounted on a drive plate that revolves around the electrode wire. The rolls are skewed at a slight angle so that with each revolution of the drive plate the wire is propelled the amount of pitch or skew of the drive rolls. Figure 11-17 shows the theory of operation. A nut revolving, but without linear motion, pushes the threaded rod forward. This system allows the wire feed head to be miniaturized. It uses three drive rolls and is called a linear wire feed system. Changing the skew angle of the drive rollers is similar to changing the gearbox ratio of a conventional wire feeder. This system is self-regulating and it is possible for a linear feeder to be used in an extended cable to propel the electrode wire very long distances. The linear feeder is very small and can be enclosed inside the welding gun. It can feed small-diameter wires up through the largest used for welding. A different drive roller pitch is used for each different wire size. The wires pass through the hollow shaft of the drive motor. This feeder also acts as a wire straightener. The linear system has been used successfully for feeding extended lengths of aluminum electrode wire.[2]

The other two types are normally used for cold wire feed systems. One is known as the capstan system, where the electrode wire is in contact with a large drive roll around its complete circumference. The electrode wire is kept in contact with the large drive roll with numerous

Power Source Type	Electrode Wire Feeder Type: Voltage Sensing	Electrode Wire Feeder Type: Constant Speed
CV direct current	Difficult to adjust; seldom used; self-regulating within limits	Best for gas metal arc welding; best for flux-cored arc welding; best for submerged arc when using small-diameter electrode wire; self-regulating
CC direct current	Best for submerged arc when using large-diameter electrode wire; used for GMAW on aluminum; self-regulating	Difficult to control; not used for small wire GMAW; not self-regulating
CC alternating current	Used for submerged arc (medium and large electrode diameters); used for flux-cored arc welding; self-regulating	Difficult to control; not used for GMAW; not self-regulating

FIGURE 11-16 Power source type versus wire feeder type.

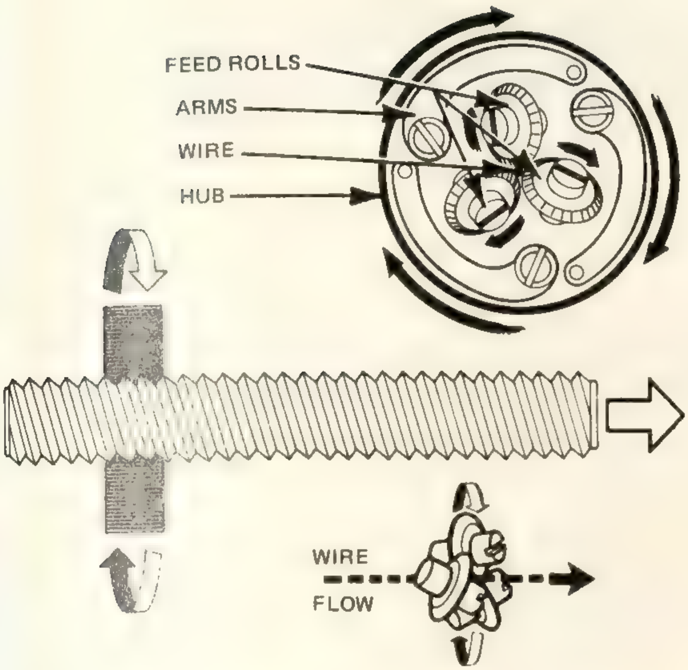


FIGURE 11-17 Principle of planetary-linear wire feeder.

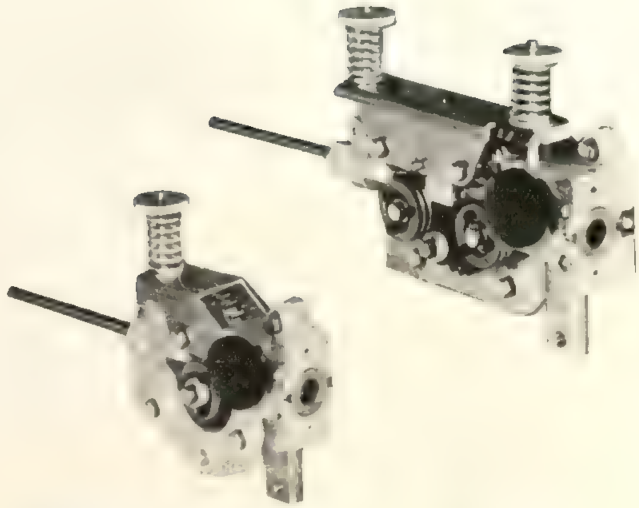


FIGURE 11-18 Pinch roll drive, two or four rolls.

pressure rolls. The action is similar to the capstan on a ship for handling deck loads with ropes. Another system is known as a multigrip system, where pressure rolls hold the electrode wire against a larger drive wheel. In this case, the electrode wire is in contact with approximately 60° of the circumference of the drive roller. Other feeders have been developed with short-stroke incremental feeding, but this type has not become popular.

The most popular type of feeding system uses pinch rolls, which transmit the feed motor rotary power to the electrode wire to push it in a linear motion. The pinch rolls grip the wire on opposites sides, and by means of pressure provide positive linear motion (Figure 11-18). Two roll drives are most commonly used. Light-duty feeders use two drive rolls and only one roll is powered. Heavy-duty feeders use two drive rolls and both are powered. For special applications four drive rolls are used and all four are powered. The advantage of the four drive rolls is that less pressure is required on the electrode wire. This is particularly important when feeding flux-cored electrode wire since the sheath of the wire may collapse if the pressure is too great.

The design of the driving surface of the rolls is extremely important. Different-type rolls are used for different types and sizes of electrode wires. The drive rolls are steel and approximately 2 in. in diameter. The different driving surfaces are:

- ☐ Flat-smooth
- ☐ Flat-knurled
- ☐ Smooth-vee
- ☐ Knurled-vee
- ☐ U groove
- ☐ Cog wheel

The groove in the drive rolls is important and relates to wire drive efficiency. The U-shaped grooves are not recommended because of problems with the electrode diameter, which can vary by ±0.001 in. If the electrode wire is too large, it will not fit into the groove or may require too much force. If the wire is too small, it will slip in the groove and accurate feeding will not occur. The V groove has advantages over the flat drive rolls in that there are four points of contact rather than two. This provides better control and better transfer of power to the electrode wire. In some cases the drive rolls are made as two individual pieces, which can be reversed to provide a new surface to replace worn surfaces. Figure 11-19 provides selection information for electrodes of hard wire, soft wire, and tubular wire of different sizes. Hard wires are made of steel, stainless steel, and nickel alloys. Soft wires are made of aluminum, magnesium, and copper. Tubular wires are flux-cored electrode wires. The method of applying pressure to the wires should be positive but adjustable. Rolls should be adjusted so that they do not slip on the wire and do not deform the wire. Knurled rolls tend to indent the wire, which makes it more abrasive when going through conduits and current pickup tips. If too much pressure is used, it will deform the wire and possibly stall the drive motor. If too little pressure is used, slippage will occur.

The wire feed motors for heavy-duty wire feeders have up to ¼ horsepower. Smaller motors of ⅛ or ⅒ horsepower are often used. Smaller motors are used for the hand guns, and the linear systems use a small motor with a hollow shaft. Most feed motors are of the dc shunt

ELECTRODE WIRE DIAMETER		ELECTRODE WIRE TYPES					
in.	mm	Hard Wire	Hard Wire	Hard and Tubular Wire	Soft Wire	Hard and Tubular Wire	Tubular Wire
0.024		X	X	–	X	–	–
0.030	0.75	X	X	–	X	–	–
0.035	0.9	X	X	–	X	–	
0.045	1.1	X	X	–	–	–	
3/64 (0.047)	1.2	–	–	–	X	–	
0.052	1.3	X	X	–	X	–	X
1/16 (0.063)	1.6	–	–	X	X	X	X
5/64 (0.078)	2.0	–	–	X	X	X	X
3/32 (0.094)	2.4	–	–	X	X	X	X
7/64 (0.109)	2.8	–	–	X	X	X	X
1/8 (0.125)	3.2	–	–	X	X	X	X
5/32 (0.156)	4.0	–	–	–	–	X	X
3/16 (0.188)	4.8	–	–	–	–	X	X
7/32 (0.219)	5.6	–	–	–	–	X	X
1/4 (0.250)	6.4	–	–	–	–	X	X
FEED ROLLS SELECTION		Flat – Smooth	Flat – Knurled	Smooth Vee	Smooth Vee	Knurled Vee	Cog
		Smooth Vee	Smooth Vee	Smooth Vee	Smooth Vee	Smooth Vee	Cog

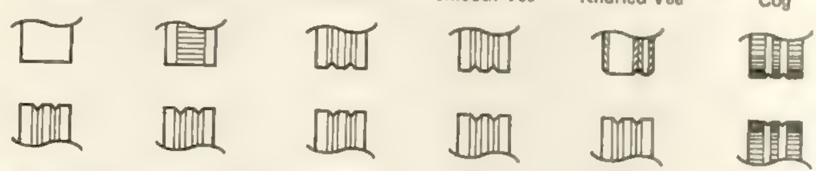


FIGURE 11-19 Drive roll selection chart.

type; however, permanent-magnet motors, stepper motors, pancake motors and print motors are all used. The resistance to the motor is the drag on the wire as it passes through the conduit, drive rolls, and current pick-up tube. If there are kinks in the electrode wire, additional resistance is encountered. A problem with wire feed motors in automatic systems is the need to pull wire from large spools. This causes high-inertia loads, and the life of the wire feed motor may be shortened. This can be overcome with special wire dispensing methods.

Each welding procedure has a specific electrode wire feed rate, given in inches per minute, millimeters per minute, and sometimes, meters per hour. Wire feeders have a range of wire feed speeds that can be adjusted. A typical minimum feed rate is 50 in. (127 cm) per minute and the maximum is 1000 in. (2540 cm) per minute. This speed range would be ample for most welding applications. This range is very broad and normally requires gearbox changes. Manufacturers' data sheets provide the maximum and minimum wire feed rates available for different-model wire feeders with different gearbox ratios, maximum and minimum size of electrode wire, and the different types that can be used with a particular wire feeder. The data sheets also provide the speed regulation and the length of conduit that can be accommodated by a particular wire feeder. The wire feeder should have a speed range that includes the range of wire feed speeds for the welding conditions that are to be used. The speed regulation of the feeder indicates how much the wire feed motor will slow down when extra resistance is placed on the feeding of the electrode wire.

As an aid in selecting a wire feeder, see the charts showing the feed speeds of different electrode types used with different welding processes. Figures 11-20 to 11-22 show the wire feed speed versus welding current. Figure 11-20 is for the gas metal arc and flux-cored arc welding process using solid and tubular small-diameter steel wires. Figure 11-21 is also for GMAW but for nonferrous elec-

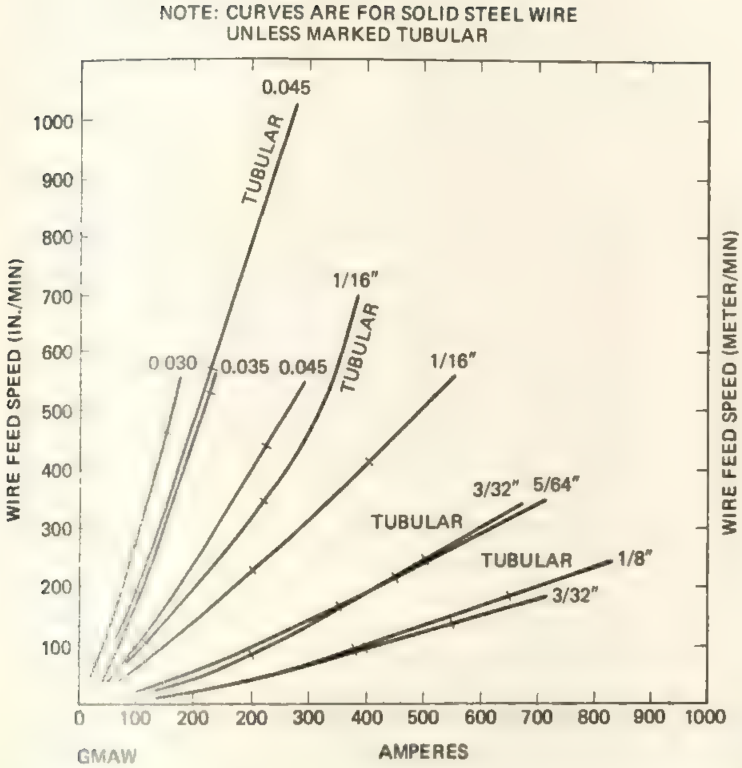
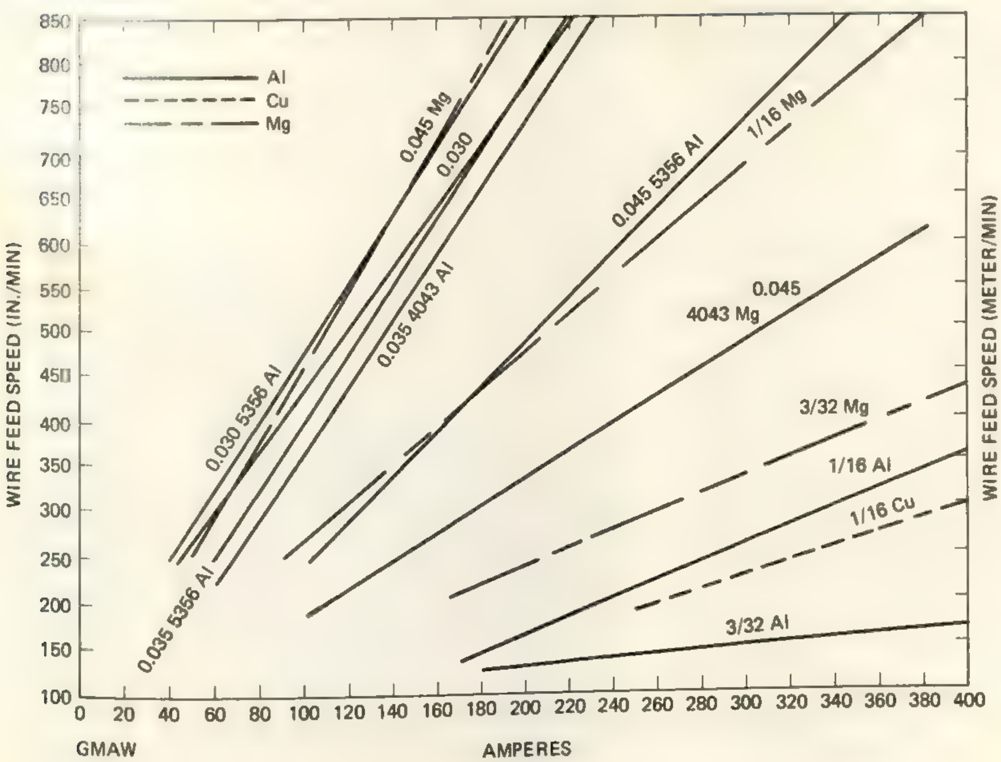


FIGURE 11-20 Steel electrode wire (GMAW and FCAW).

FIGURE 11-21 Steel electrode wire with submerged arc.



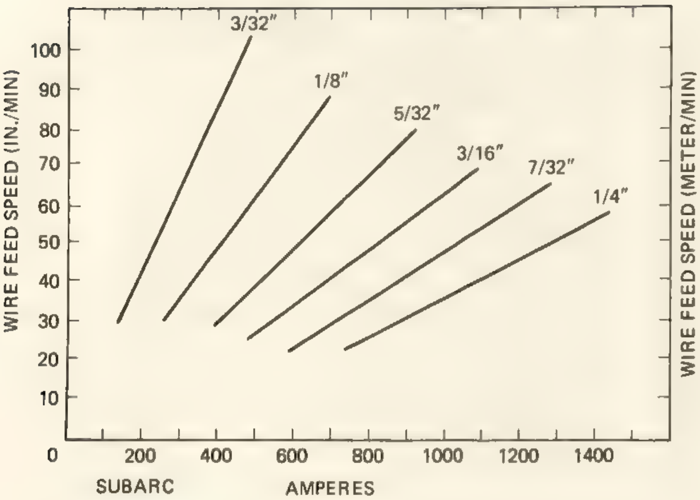


FIGURE 11-22 Nonferrous electrode wire (GMAW).

trode wires. Figure 11-22 is for steel electrode wires, used with submerged arc welding.

Wire drive mechanisms, or feedheads, are also used in automatic welding systems. Normally, the feedheads are the same as those in a heavy-duty semiautomatic system. For automatic welding a more complicated control system is used. Mounting hardware is available for attaching the feedhead to motion devices or in fixtures for specific applications.

Wire Handling and Dispensing Systems

The wire feeding or electrode wire dispensing equipment should accommodate the package type of the electrode wires purchased. Welding electrode wire, solid or tubular, comes in different packages to suit the needs of the production operation. In general, they come packaged on small and medium-size spools, small coils, reels, drums, or payoff packs and very large coils. Small spools are used on manually held welding guns. Medium-size spools normally require a spool adapter, which is designed to fit the inside diameter of the spool and engage a hole in the spool. This will provide a braking function so that wire does not unwind from the spool. Small coils require an adapter or spider to center and retain the coil and allow uniform unwinding. These items are available from the wire feeder supplier.

Large reels require special dispensing equipment. These reels come with from 250 to 1000 lb of electrode wire. The reels are made of wood with holes for an axle. The larger reels can be unwound with the axis horizontal, in which case an axle must be inserted in the reel and carried on a dereeling device. There are two general types of dereelers with a horizontal axis. One dereeler allows the wire feeder to pull the wire and rotate the reel. It may incorporate a brake to stop the reel when the wire feeder stops, to avoid unwinding and overlapping of loops, which may cause tangles. Wire feed motors are designed to utilize relatively small spools or coils which have relatively low inertia loads when starting to unwind. The larger reels with a large amount of electrode wire are quite heavy, and the inertia loads for starting a reel in rotation are high and may cause premature failure of wire feed motors. A motorized dereeler (Figure 11-23) should be used. When the wire feed motor exerts a pull on the supply reel, the dereeler motor starts to rotate the reel. It has a variable-speed motor which matches the speed of the wire feed motor. This reduces the load on the wire feed motor and improves wire feed motor life. An extra load on the wire feeder can also occur if the electrode supply is remote from the wire feeder and the electrode wire is fed through conduits or similar devices. This extra resistance load on the wire feed motor can be overcome by utilizing a motorized dispensing system. Motorized dispensing systems will also assist in arc starting, particularly when the reel is full.

Electrode wire comes in large coils of up to 1000 lb on a pallet. To feed wire from the coil, a dispenser with a rotating arm (Figure 11-24) is used. These rotary dispensers are used for $\frac{1}{16}$-in.-diameter and smaller solid or covered electrode wire. The arm rotates around the axis of the coil and there is no inertia load since the coil remains stationary. An adjustable drag brake prevents premature release of the wire, eliminating tangling. The wire may be carried in a conduit to the wire feeder. The problem with this type of dispenser is that it introduces one rotation of twist into the electrode wire for each revolution of the arm. This may cause wandering of the arc as the electrode wire twists in feeding from the tip of the welding torch. This can be overcome with a rotary motorized wire straightener.

FIGURE 11-23 Motorized dereeler.

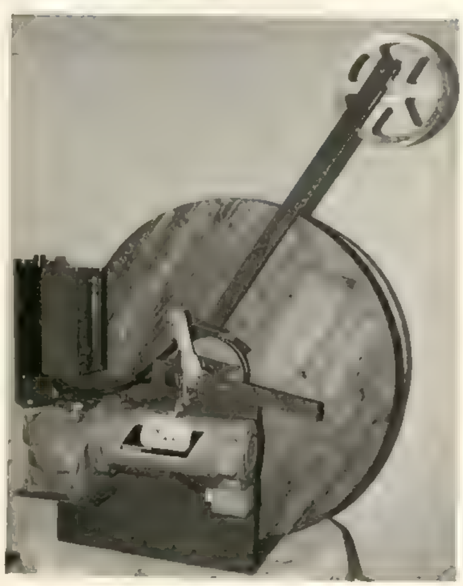


FIGURE 11-24 Rotary dispensers for large coils.

Another method of purchasing welding electrode wire is in a drum or payoff pack. The drums, made of heavy cardboard, will contain 250, 500, or over 700 lb of electrode wire. A special dereeling system for drums is shown in Figure 11-25. It sits on top of a drum and utilizes a rotating pickup arm and a pulley system to feed the wire to the wire feeder. There is no inertia since the supply of wire does not rotate. The electrode wire twists

FIGURE 11-25 Dispenser for wire in drums.

one revolution per loop as it is unwound. A rotary wire straightener will overcome this problem.

Another method of dispensing wire from a drum or payoff pack is by means of a rotating table which revolves the wire as it is unwound. This eliminates the twist to the wire. A special control system and rotating device are required.

It is important to match the dispensing method to the automatic welding system. The expense of the system must be justified by the cost savings of purchasing the electrode wire in larger quantities and packages and the maintenance cost of the wire feed heads.

Wire Feeder Maintenance

Periodic inspection and preventive maintenance will reduce downtime and assure maximum service from the wire feed system. The control circuitry should be cleaned by blowing out with dry air at 25 to 30 psi every three months. Relay contacts and other sliding connections should be checked. The electrical connections, particularly plugs, that are connected daily should be inspected periodically. The grease in the gear case should be changed at least every 500 hours of operation. The housing should be flushed and new grease of the same type should be installed. The wire feed motors should be inspected and the brushes replaced according to wear. The commutating surface of the armature should also be checked, and if the surface appears rough or worn, it should be polished.

Gun cable assemblies, when used, should be blown out once a day so there is no accumulation of dirt in the electrode wire conduit. The gun, especially the electrode tip and nozzle, should be checked daily and replaced as required. Drive rolls should be checked weekly and replaced as required. Most manufacturers provide troubleshooting checklists for investigating equipment stoppages. Maintenance work should be done by qualified people.

11-3 WELDING CABLES AND CLAMPS

Welding cables are the electrical conductors, normally called the electrode lead and the work lead. These leads carry the welding current from the power source to the arc at the point of welding, and back to the power source. The cables along with the electrode holder and work connection complete an electrical circuit.

The welding circuit can be a source of power waste and an economic loss, as well as a source of weld quality problems due to erratic operation. Power losses might result from the following:

1. Loose connections at the power source
2. Loose connections at the work connector or electrode holder

3. Poor-quality repair splices in the cable
4. Use of cable in which strands are broken and the cable is not properly repaired with a splice
5. Use of cable too small for the amperage or duty cycle being used
6. Enlarging the hole in a cable lug to fit a larger stud size
7. Use of excessively long cables which cause abnormal voltage drop

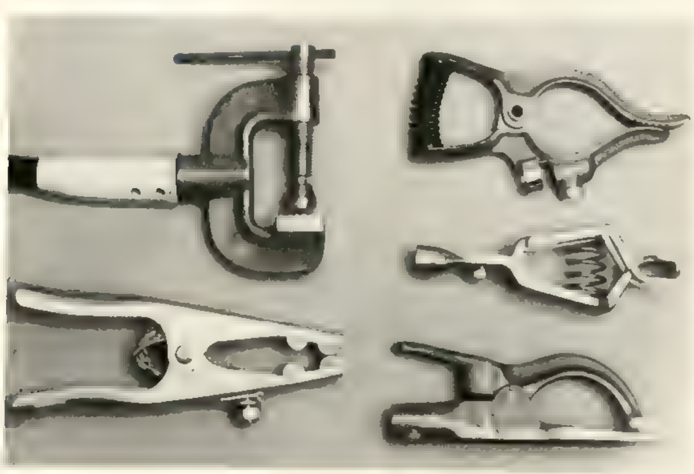
As the price of electrical energy increases it becomes extremely important to *inspect* and *maintain* welding conductors and the total circuit at peak operating efficiency! A hot point anywhere in the welding circuit is a source of high resistance, a point at which current is being wasted.

It has been found that if 10% of the strands of a cable are broken, the operating temperature of the cable can rise approximately 10 °F (5.5 °C). Cables will still carry welding current with up to 30% of the strands broken, but the operating temperature can rise 30 °F (16.6 °C). An easy way to check for damaged cables and points where power is wasted is by checking for hot spots by feel.

The work connection, erroneously called a ground clamp, is an important part of the welding circuit. There are several different types of connections available ranging from spring clamps to actual welded-on connections. Figure 11-26 shows different types. Many styles come in different sizes and are rated according to current-carrying capacity. These connectors should be checked routinely to see that there is not an excessive voltage drop between the cable and the work.

Connectors for splicing additional lengths of cables are commercially available. These allow for quickly increasing or decreasing the lengths of leads. The connectors must be properly attached to the leads and must be well maintained to avoid excessive voltage drops at the connection. Connectors must be fully insulated.

FIGURE 11-26 Variety of work connection clamps.



Welding Cable Size Designation

In North America, electrical conductors and cables are specified in size by the American Wire Gauge (AWG). The AWG numbers range from a small size such as number 54 gauge (ultrafine magnet wire) to cables so large that they are designated by MCM (thousands of circular mils). Wire such as number 12 gauge or number 14 gauge may be encountered in the wiring of a house. Welding cable sizes range from number 6 gauge through number 4/0 (pronounced "four ought"). The cable sizes for welding are shown in Figure 11-27. The two largest sizes are 250 MCM and 300 MCM. The term mil refers to 0.001 in. One circular mil equals the area of a circle whose diameter is 0.001 in.

Outside North America, welding cable is specified in metric size. The relationship between metric and the American Wire Gauge is shown in Figure 11-27. Note that these are not soft conversions or exact comparisons since the nominal circular mils areas are not equal. The chart shows the metric size, which is its cross-sectional area in square millimeters. The overall diameter includes the jacket. The dimensions and characteristics given may vary between suppliers because of tolerance and differences in standards.

Welding cables are made of many strands of fine drawn, annealed copper. The copper in this form provides maximum flexibility of the welding cable. A separator, such as paper or Mylar-foil is placed between the copper strands and the insulation or jacket. This separator is an aid to jacket removal at terminations. Jacket compounds are designed to be flexible and to protect the copper conductor from the shop environment. These jackets are made of variations of synthetic rubber which do not melt when they come into momentary contact with sparks or hot metals.

Welding cables are normally made of copper; however, aluminum welding cables are available. Aluminum cables have the advantages of being lighter in weight and are less likely to be pilfered. Disadvantages are that normally two AWG sizes larger must be used than would be used in copper to compensate for the lower conductivity of aluminum. Termination is more difficult and critical, and the flex life of aluminum cables is considerably less than that of copper. Aluminum cables should be used for low-duty-cycle welding applications or where the cable is not normally flexed during the welding operation.

The arrangement of the strands within the cable has an influence on flexibility. Rope terminology is used to define these arrangements. A *rope lay* has all the strands, groups of strands, and group layers cabled in the same direction. There are seven groups of fine strands, six of

American Wire Gauge (AWG) Size	Nominal Overall Dia. in inches	Approx. Wt. per 1000 ft in Pounds	Resistance DC per 1000 ft @ 68° F in Ohms	Area in Circ. Mils	Metric Nominal Cross-Sectional Area mm^2	Overall Diameter mm	Approx. Wt. per 1000 meters in kg	Resistance Ohms per 1000 m
8	0.340	121	0.688	16510				
				19740	10	10.5	130	1.75
6	0.390	137	0.435	26240				
				31580	16	11.5	235	1.09
4	0.440	194	0.272	41740				
				49350	25	13.0	330	0.70
2	0.550	306	0.173	66360				
				69100	35	14.5	440	0.50
1	0.600	376	0.137	83690				
				98700	50	17.0	610	0.35
1/0	0.660	464	0.109	105600				
2/0	0.715	563	0.087	133100				
				138200	70	19.5	840	0.25
3/0	0.785	708	0.068	167800				
				187500	95	22.0	1120	0.18
4/0	0.875	884	0.054	211600				
				237000	120	24.0	1410	0.146
250 MCM	0.980	1070	0.045	250000				
				296000	150	26.5	1690	0.117
300 MCM	1.060	1260	0.038	300000				
				365000	185	29.0	2100	0.094

FIGURE 11-27 American and metric cable size comparison.

which are cabled around a center group. This will produce a conductor having the correct combination of service life and flexibility at a reasonable cost. For extreme limpness a *hawser lay* is used. In this configuration each layer or group of strands is cabled in the direction opposite to the covering layer. Hawser lay cable provides greater flexibility and can be used for a short portion of the lead at the electrode holder. It is more expensive than the rope lay cable.

What Cable Size to Use

To determine what size of welding cable to use, refer to Figure 11-28. Three items must be considered:

1. The welding current
2. The duty cycle or operator factor
3. The total length of the welding circuit

This means the total distance from the power source to the work and return. The 100-ft column means that the work is 50 ft from the power source. As the distance increases the cable size should increase. This is to compensate for line loss within the cable due to increased length.

The chart also shows the duty cycle or operator factor which will be involved. This table assumes two categories; (1) up to 60% duty cycle, and (2) from 60 to 100%. Semiautomatic welding is in the top portion of the lower-duty-cycle range, whereas automatic welding is in the higher-duty-cycle range. The voltage drop in the welding circuit should not exceed 4 V.

There are three methods to determine the amount of power lost in the welding leads. In the first method, use an accurate voltmeter and measure the voltage at the welding machine terminals and the voltage between the electrode holder and the work connection while welding. Also, measure the welding current. The difference between the voltage at the power source terminals and at the electrode holder and work connection is the voltage lost in the leads. When multiplied by the welding current, this gives the amount of power lost in the leads. This is in accordance to the following formula:

$$\text{power loss} = V_1 \text{ (at terminals)} - V_2 \text{ (at holder)} \times I$$

or

$$PL = V_1 - V_2 \times I$$

An example would be 35 V measured at the terminals and 32 V measured between the electrode holder and the work connector or 3 V × welding current of 250 A = 750 W lost.

A second way to determine power loss is to find the resistance of the welding cables and multiply this by the

Weld Type	Welding Current	Length of Welding Cable Circuit in Feet—Cable Size A.W.G. 50 ft	100 ft	150 ft	200 ft	300 ft	400 ft
Manual or semiautomatic welding (up to 60% duty cycle)	75	6	6	4	3	2	1
	100	4	4	3	2	1	1/0
	150	3	3	2	1	2/0	3/0
	200	2	2	1	1/0	3/0	4/0
	250	2	2	1/0	2/0	4/0	—
	300	1	1	2/0	3/0	—	—
	350	1/0	1/0	3/0	4/0	—	—
	400	1/0	2/0	3/0	—	—	—
	450	2/0	3/0	4/0	—	—	—
	500	3/0	3/0	4/0	—	—	—
Semi or automatic welding (60% to 100% duty cycle)	400	4/0	4/0	—	—	—	—
	800	2-4/0	2-4/0	—	—	—	—
	1200	3-4/0	3-4/0	—	—	—	—
	1600	4-4/0	4-4/0	—	—	—	—

The length of the cable circuit is the length of the electrode lead plus the length of the work lead.

FIGURE 11-28 Copper welding cable size guide.

welding current squared. The resistance of the different sizes of cables is shown in Figure 11-27. Modify data by total cable length. The formula is

$$PL = I^2R$$

A third way is by the use of Figure 11-29. This provides the voltage drop for each cable size, based on a 100-ft-long circuit when welding at the current shown. In this case the power loss equals the welding current times the voltage drop or $PL = I \times VD$. These data would be factored according to the length of the cable circuit.

Termination Technique

The connection of the cable to the terminal lugs, the electrode holder, and to the work connector are potential sources of high resistance. Therefore, they should be made as efficient as possible. If any of these connections become hot, the joint should be reworked. Soldering the cable to the lugs, and so on, is one way to achieve a highly efficient joint. The thermit welding process can also be used for joining cable to special lugs. Mechanical fastenings are also employed; however, these may become loose and must be retightened to maintain a low-resistance joint.

Welding Current Amps	Voltage Drop per 100 ft of Lead vs. Cable Size (AWG) #2	#1	#1/0	#2/0	#3/0	#4/0
50	1.0	0.7	0.5	0.4	0.3	0.3
75	1.3	1.0	0.8	0.7	0.5	0.4
100	1.8	1.4	1.2	0.9	0.7	0.6
125	2.3	1.7	1.4	1.1	1.0	0.7
150	2.8	2.1	1.7	1.4	1.1	0.9
175	3.3	2.6	2.0	1.7	1.3	1.0
200	3.7	3.0	2.4	2.0	1.5	1.2
250	4.7	3.6	3.0	2.4	1.8	1.5
300	—	4.4	3.4	2.8	2.2	1.7
350	—	—	4.0	3.2	2.5	2.0
400	—	—	4.6	3.7	2.9	2.3
450	—	—	—	4.2	3.2	2.6
500	—	—	—	4.7	3.6	2.8
550	—	—	—	—	3.9	3.1
600	—	—	—	—	4.3	3.4
650	—	—	—	—	—	3.7
700	—	—	—	—	—	4.0

FIGURE 11-29 Voltage drop for different cable size per 100 ft of welding cable.

Power Cable

The power cable is the conductor used to carry the electrical power from the disconnect or fuse box of the building to the welding power source. Three-conductor cable is usually used for this application; however, four-conductor cable is sometimes used when the welding machine is on a portable mounting. The fourth wire is used to ground the case of the machine to earth.

The basis for determining the size of power conductor cables is the input power required by the welding machine. A factor to consider is whether the machine operates on single-phase or three-phase power. Figure 11-30 shows the three-conductor power cable size guide for welding machines. It provides size requirements for motor-driven three-phase welding machines and single-phase transformer–rectifier power sources. The power cables are rated at a higher voltage than welding cables since input power to machines can be 480 V or higher. The name plate of the welding machine will provide the amperage drawn at the rated load and input voltage of the machine. This information is also shown on the data sheets of the machine, available from the manufacturer.

The normal color coding for three-conductor power cables is black, white, and green and for four-conductor cables is black, white, green, and red. The size of cables, their diameter, and weight are presented in Figure 11-31. These cables are flexible tinned-copper conductors with paper separators jacketed with insulation suitable for this voltage requirement.

Safety Considerations in the Use of Welding Cable

Welding cables are designed to be used only in conjunction with the relatively low voltages typical of welding equipment. Welding cable should not be used at power-line voltage or for other power applications. The Occupational Safety and Health Act contains specific requirements that apply to the use of arc welding equipment. Some OSHA safety requirements:

1. Coiled welding cable must always be spread out before using to avoid overheating during use.
2. Cables must not be spliced within 10 ft of the holder.
3. Welding electrode cable must never be coiled or looped around the body of a welder.

Input Ampere of Welding Machine at Rated Output			Three Conductor Power Cable Wire Size A.W.G.
Motor Driven Three Phase	Rectifier or Transformer Single Phase	Rectifier or Transformer Three Phase	
up to 24A	up to 30A	up to 24A	10
24 to 32A	30 to 40A	24 to 32A	8
32 to 44A	40 to 55A	32 to 44A	6
44 to 64A	55 to 70A	44 to 64A	4
64 to 76A	70 to 95A	64 to 76A	2
76 to 88A	95 to 110A	76 to 88A	1
88 to 100A	110 to 125A	88 to 100A	1/0
100 to 130A	125 to 165A	100 to 130A	2/0
130 to 155A	165 to 195A	130 to 155A	4/0

FIGURE 11-30 Copper power cable size guide.

FIGURE 11-31 Power cable size information.

Size Awg	No. of Conductors	Stranding No. Wires Gauge	Insulation Thickness (in.)	Sheath Thickness	Approx. Outside Dia. in.	I.P.C.E.A.* Amp Rating	Approx. Net. Wt. (1000 ft)
10	3	105 X 30	3/64	Type S	0.700	25	305 lb
8	3	132 X 29	4/64	6/64	0.835	35	440 lb
8	4	132 X 29	4/64	6/64	0.915	35	538 lb
6	3	132 X 27	4/64	6/64	0.900	45	567 lb
6	4	132 X 27	4/64	6/64	1.010	45	705 lb
4	3	259 X 28	4/64	Type W	1.17	65	1050 lb
4	4	259 X 28	4/64	Type W	1.27	55	1295 lb
2	3	413 X 28	4/64	Type W	1.34	90	1275 lb

*Insulated power cable engineers association.

4. Cables with damaged insulation must be repaired or replaced.
5. Welding cables must only be joined together by means of recommended connections.

11-4 AUXILIARY WELDING EQUIPMENT

There are a number of auxiliary devices employed in mechanized welding systems that greatly improve the operation of the system.

Wire Straighteners

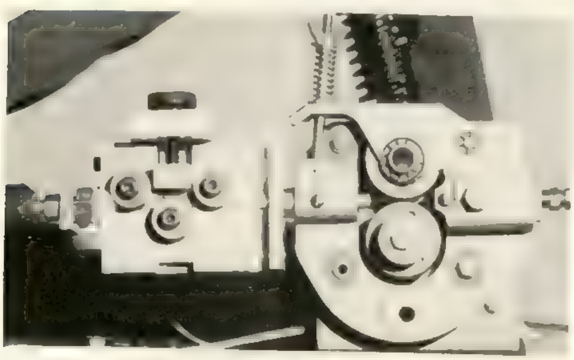
Wire straighteners are often required for automatic systems. A wire straightener is used to remove the inherent cast and helix of the spooled or coiled electrode wire and make it straight. Two three-roll wire straighteners arranged in two planes will remove the majority of the cast and helix from the electrode wire. Wire straighteners of this type (Figure 11-32) are usually placed downstream from the wire feeder so that the electrode wire extending from the end of the torch contact tip will come out straight. This is to prevent arc wander of the wire after leaving the contact tip.

Rotary wire straighteners (Figure 11-33) are sometimes used. They must match the electrode size and type. They require a motor to provide rotational motion. In a rotary wire straightener the electrode wire runs through a bent tube which is continuously rotating.

Nozzle Cleaners

A torch cleaner, normally automatic, is often used in robot arc welding systems. The nozzle of the torch is close to the arc and will gradually pick up spatter. Spatter adheres to the nozzle and in time reduces the effectiveness of the nozzle to direct the shielding gas. The robot controller can be programmed to move the torch to the cleaner periodically and remove the accumulated spatter. There are also "blow-down" systems which attempt to remove spatter by an air blast. Some cleaners also will spray or dip the nozzle into antispatter material to reduce the frequency of cleaning required. These mechanical cleaners can be made automatic so that they operate only when the program calls for it.

FIGURE 11-32 Three-roll wire straightener.



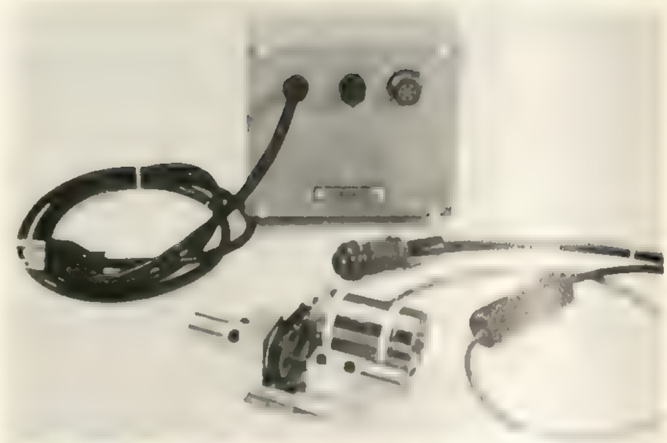


FIGURE 11-33 Rotary wire straightener.

Water Coolers/Circulators

Cooling water is commonly used for many heavy-duty welding operations. Most plasma torches require cooling water; heavy-duty gas tungsten welding and high-current gas metal arc require water-cooled torches. Electroslag and electrogas retaining shoes are often water cooled. In addition, backing bars in seamers and heat sinks in fixtures often require water cooling. Water coolers/circulators are of two basic types. One system utilizes a pump that circulates water through the torch or item to be cooled to a reservoir. The volume of water in the reservoir is large enough so that the torch is kept relatively cool. The circulator type of system is recommended for light-duty work only, since the water in the system will gradually rise in temperature until it reaches the boiling point. For certain types of work, particularly low-current plasma and gas tungsten arc welding, stainless steel tanks and tubing are required. In some cases deionized water must be used.

For heavy-duty work such as high-current welding or cooling retaining shoes, large-volume high-capacity heat exchangers are required. When a large amount of heat is generated over a long period, the heat must be extracted from the system and the water must be cooled by means of a heat exchanger or radiator. This is necessary to maintain a uniform cool operating temperature of the cooling water. Water cooler circulators are rated by the heat extraction rate, in Btu per hour. For light-duty welding in the medium-current range, a 25,000-Btu/hr unit is recommended. For heavy-duty work, a 50,000-Btu/hr unit is recommended. The circulator should be rated so that the temperature of the water does

not exceed 150°F. The water-cooling circulator should have an adjustable flow rate control, a flow or pressure switch, an interlock circuit, and a fan circulating air through the radiator. It should also allow for adjustable pressure. All flow switches, pressure switches, and interlocks should be connected to the welding control circuit. For many applications the tank and piping system should be noncorrosive. The minimum flow rate should be at least ½ gallon per minute, and adjustable up to 4 gallons per minute. There should be sufficient water capacity in the system so that if a leak occurs, it will not immediately cause a burnout. Circulators are sometimes incorporated in the control cabinet or in the welding power source. It is important to specify the size heat exchanger required for a particular application. It is better to overspecify and have excess capacity than to underspecify. Tap water to be discharged is too expensive to use.

Smoke Exhaust Systems

Smoke exhaust devices are used in many semiautomatic and mechanized welding systems. This system is based on collecting the fumes as close as possible to the point of generation. The fumes collected in the immediate area of the arc are passed through a filter and then exhausted to the outside. In some cases, the cleaned air is returned to the welding shop. This is questionable practice since the filter system removes only the particulate matter of the fume and has no effect on gases. For gas metal arc or flux-cored arc welding, a special nozzle is used on the welding gun which collects the fume from the arc area. The entire exhaust system consists of the smoke exhaust gun, cable assembly, vacuum blower, filter, and waste can. These systems greatly reduce the pollution in the air of a welding shop. Different types of pickup devices are used for shielded metal arc welding.

Miscellaneous Arc Motion Devices

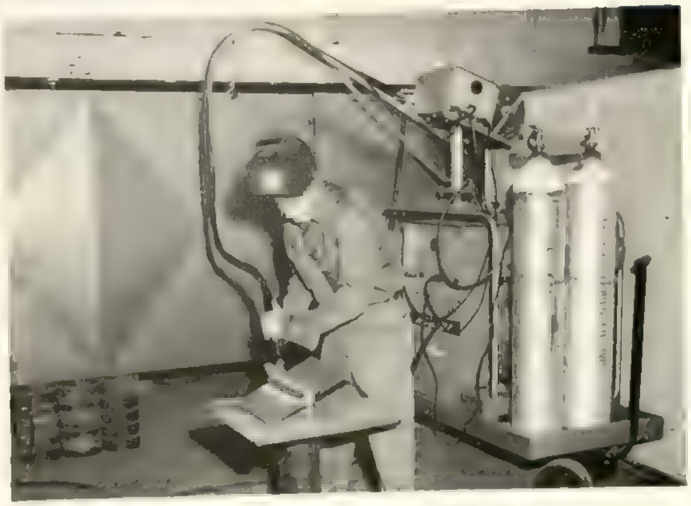
Welding oscillators or arc weavers are devices that provide transverse motion to an arc. These units provide a wider welding bead for surfacing applications and are sometimes used for wide joints. Oscillators are available as components that can be added to mechanized welding equipment. There are at least two types. One has a linear motion and the other a pivoting or swinging motion. Motion is controlled by mechanical devices such as lever arms or cams or by electronic devices containing timing circuits.

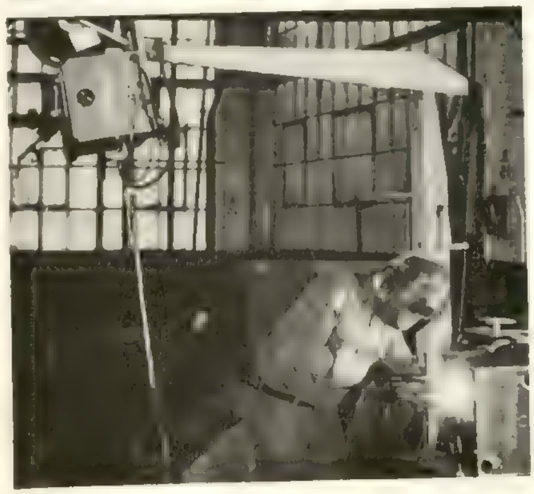
The mechanical type provides sinusoidal oscillation using an adjustable crank arm. Other types utilize cams which can be shaped to provide a specific motion that can include a dwell time at the end of each oscillation stroke. The mechanical cam or crank arm types are difficult to adjust during operation. The newer types with electronic control can be changed easily. The dwell time at either end of the stroke can be lengthened or shortened, and the width of oscillation can be changed during operation. It is also possible to change the centerline of oscillation. The electronic control system can be used for pivoting or linear motion. If it is necessary to change any of the oscillation parameters during welding, the electronic controlled type is the best selection. If wide oscillation is required, the linear action is preferred to the pivoting action.

Portable Booms

There are a large number of devices that provide portability to the welding equipment. These are particularly popular for semiautomatic welding. These units usually include a boom or arm which supports the wire feeder so that the gun and its cable are usable over a wide area. This provides flexibility for semiautomatic welding, previously attained with shielded metal arc welding. Many of these units also carry the power supply and the electrode wire supply. Figure 11-34 shows two examples of a port-

FIGURE 11-34 Portable booms for semiautomatic welding.





able mounting for semiautomatic welding. The various types provide different features, and selection is largely a matter of personal preference.

11-5 INSTRUMENTS FOR WELDING INFORMATION

Instruments required to obtain information about a welding operation are many and varied. They relate to the welding process and the degree of precision required. Originally, shielded metal arc welding was monitored by a volt meter, an ammeter, and a stopwatch to measure travel speed. Manual welding procedures were developed and monitored with panel meters of the welding machines. Manual welding is rarely monitored by recorded meters, and it is generally agreed that manual welding is based more on operator skill and ability rather than on strict procedures.

Arc welding is shifting more toward automation and quality requirements are becoming more stringent. It is necessary to measure accurately all the parameters involved. This requires the use of suitable, accurate measuring instruments.

The newer welding processes and the complex procedures have more variables than manual shielded metal arc welding. To qualify a welding procedure, it is necessary to measure and record all the parameters and variables. To duplicate the welding procedure, it is necessary that these parameters and variables be the same as the original procedure. This has brought about the need for more accurate measuring instruments and the need to measure variables heretofore ignored.

The welding procedure requires accurate measurement of at least the following:

- ☐ Arc voltage, welding current, travel speed
- ☐ Electrode wire feed speed
- ☐ Shielding gas flow rate
- ☐ Arc time
- ☐ Pulsing parameters, including peak current, background current, peak current time, background current time, and frequency
- ☐ Ramping or change rates of current with respect to time
- ☐ Wave shape or form

Welding machine panel meters are not suitable for accurate measurement of arc voltage and welding current. Their accuracy is less than desired, the scale is too coarse, and they are hard to read. For welding voltage the panel meter must show open-circuit voltage, but the welding voltage is much smaller, usually one-half to one-third. Laboratory meters should be used.

Early methods to measure and record these parameters utilized recording meters with moving paper charts and ink pens. An example is shown in Figure 11-35. This type of equipment is satisfactory for many manual welding operations. Open-circuit voltages and high frequency in GTAW tended to complicate circuitry which led to problems with automatic recording instruments.

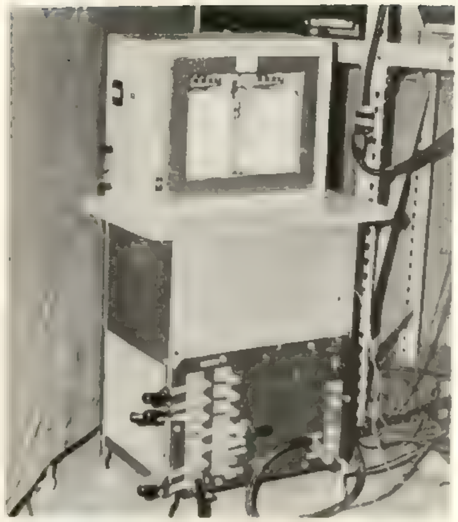
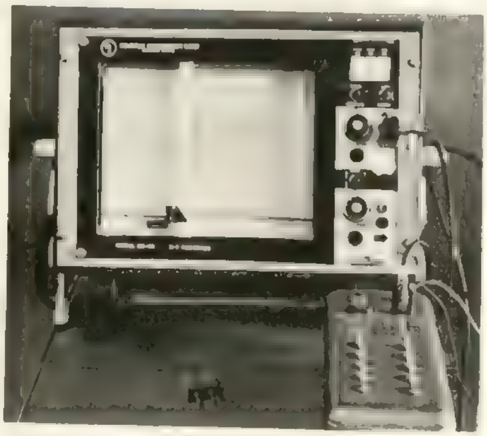


FIGURE 11-35 Moving-chart recording meter.

Other variables also needed accurate measurement: torch angle and work angle, which are normally preset; tip-to-work distance, which is preset but varies during welding; and welding machine characteristics, such as static characteristics, dynamic characteristics, inductance, and wave shape. Other factors included base metal preheat and interpass temperature measurements, and electrode or filler metals, size, type, composition, surface preparation, and so on.

High-speed recording instruments, like those shown in Figure 11-36, are utilized to measure more welding parameters and are often used for monitoring manual and semiautomatic welding of nuclear work and aerospace

FIGURE 11-36 High-speed recording instrument.



work. These instruments are much faster than ink-type paper chart recorders. Input to these machines includes arc voltage, current, wire feed speed, and travel speed. Sensing devices are used for automatic or mechanized welding to measure travel and electrode wire feed speed.

Some procedures require instruments that will detect and monitor shielding flow rates and gas purity. These devices require accurate sensing units and complex solid-state circuits to develop signals that can be read and recorded.

The problem of alternating-current wave shape is extremely complex and normally requires the use of an oscilloscope. Ac welding formerly assumed a sinusoidal waveform, and ac meters are based on this waveform. If the waveform is different, errors may be made and an oscilloscope should be used for measurements. In the case of pulsed current welding, the wave shape of the pulse is important based on the slope of the rise and fall of pulses. Frequency of pulsing is also important to determine the total energy involved.

Input power variations to welding machines have an effect on weld quality. The power-line input voltage to the power source should be monitored since adjacent machine tools or resistance welding machines may cause changes in the input voltage. Paper chart recorders are normally used.

Portable printing arc welding monitors are used that monitor up to six different variables. A system of this type is shown in Figure 11-37. This equipment is acceptable for critical work that requires printed records. The accuracy of this equipment must be checked periodically by standardized instruments.

Care must be taken to attach meter leads to the proper locations in the welding circuit. Meters and shunts must be checked for accuracy periodically. Current shunt and transformer leads must also be calibrated and cannot be spliced. Meters for welding should be damped for accurate reading.

FIGURE 11-37 Printing portable welding monitor.

QUESTIONS

11-1. What are the main functions of a welding gun or torch?

11-2. What are the differences between a gooseneck and a pistol-grip gun?

11-3. What is the advantage of a pistol-grip gun?

11-4. Why is a water-cooled gun rarely used for CO_2 welding?

11-5. What is the importance of the gun control tube or tip?

11-6. What type of contact tip should be used for welding aluminum?

11-7. Explain the two types of wire feeder controls. Which type is used with the CV machine?

11-8. What is the disadvantage of spool guns?

11-9. What factors must be considered when selecting the speed range of a wire feeder?

11-10. What is the advantage of four drive rolls when using flux-cored wire?

11-11. Why are V-groove drive rolls preferred over flat drive rolls?

11-12. Describe the characteristics of hard, soft, and tubular electrode wire.

11-13. What factors determine the size of the welding cable used?

11-14. What is the disadvantage of aluminum for welding cables?

11-15. What is indicated by a hot spot in a welding cable?

11-16. When should a heat exchanger be used in a water-cooling system?

11-17. What is the advantage of purchasing electrode wire in 1000-lb spools?

11-18. What is the disadvantage of dereeling 1000-lb spools?

11-19. What is the problem of using welding machine panel meters?

11-20. What types of meters will provide a permanent record of date?

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1. "Semi-automatic Wire Feed Systems for Arc Welding," NEMA Standards Publication EW3, National Electrical Manufacturing Association. Washington, D.C.

2. C. E. Strain and L. E. Wildenthaler, "Extended Length Continuous Wire Feed System," *Welding Journal*, May 1974.

12

Mechanized, Automated, and Robotic Arc Welding

OUTLINE

12-1 AUTOMATION OF WELDING

An arc welding system is the total combination of equipment and the means for applying it to produce a weld. This involves two basic components—the equipment or machine and an individual or human being. It has been explained that as the machine becomes more complex, the human involvement is reduced. This affects the most important cost factor, the means of applying or method of application. This was discussed in the early part of this book and shown by a chart based on original AWS definitions. This chart showed the four methods of applying a weld: manual (MA), semiautomatic (SA), machine (ME), and automatic (AU). The reduced involvement of the individual provides an improvement in the operator factor. When changing the method of application from manual to semiautomatic welding, the operator factor was increased by approximately 100%. The change from semiautomatic to machine welding also increased the operator factor, and with automatic welding the operator factor can approach 100%. This change has a major effect on the total cost.

Automatic welding became practical when the continuous electrode wire arc welding processes became popular. The advantages of automatic welding are well known and include the following:

1. Increased productivity through higher operator factor
2. Increased productivity through higher deposition rates
3. Increased productivity through higher welding speeds
4. Good uniform quality that is predictable and consistent
5. Strict cost control through predictable weld time
6. Minimized operator skill and reduced training requirements
7. Operator removed from the welding arc area for safety and environmental reasons
8. Better weld appearance, consistency of product, heavier-duty welding procedures employed, and so on.

The shift from manual welding to automatic welding and the resulting cost advantage has been known for many years. However, welding has lagged behind other metalworking operations in the transition from a manual to an automatic operation. The reason is that arc welding is a much more complex process than most other metalworking operations. Another reason is the lack of incentive to develop total automatic welding since the welded product can still be produced by the other methods of application.

The major deficiency of automatic welding is its inability to compensate for variations in welding joints in any but the simplest weldment designs. There are two potential solutions: (1) make the piece parts perfect in every respect; or (2) develop automated welding equipment which will compensate for these variations and still produce good-quality welds.

The first solution seems contrary to normal production operations. In the past, variations have been allowed to collect in the manufacturing processes and the welder would overcome the accumulated tolerances and still produce a good-quality weldment. The welder would compensate for variations, utilizing the skill and attention of the human. This is a closed-loop welding system that overcomes the problems of variations in material, variations in piece part preparation, and so on.

Automatic welding is an open-loop system unable to make needed compensating changes. The solution is to develop a closed-loop system to produce a good-quality weld in spite of variations. This requires a new method of application called "automated" or "adaptive" welding. It is a step beyond automatic welding since it involves complete control of the operation, including accommodations for poorly fitted joints, for joint preparation errors, for warpage problems, and so on. The difference between automated welding, which can be considered a closed-loop system, and automatic welding, which is an open-loop system, is the use of feedback adaptive controls plus sensing devices.

Recent events have aided the development of welding automation. The most important is the computer to control process motion and the retention of this in memory; the development of power electronics, making welding equipment computer controllable; the development of robot and precision motion devices; and the development of sensors which detect changes to modify welding programs. These developments led initially to robotic arc welding, but also to the overall automation of welding.

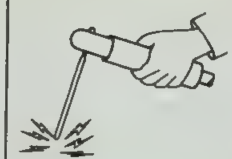
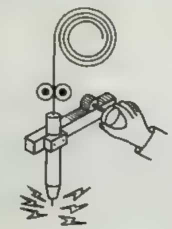
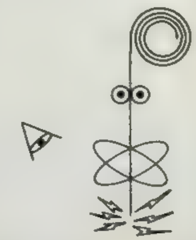
The original chart showing the application of welding versus the human–machine relationship is replaced by the new chart shown in Figure 12-1. This new chart more thoroughly describes the functions involved in making a weld, and it adds the automated, or adaptive, method of application. It also shows that manual, semiautomatic, and machine welding methods are closed-loop systems because of the human involvement. The fourth method, automatic welding, is not under constant supervision of an individual and so is an open-loop system. The functions involved in making an arc weld is expanded and show whether they are controlled by the individual or by the machine. These functions affect the level of fatigue of the individual. When more of these functions are taken over by the machine, fatigue levels are reduced and productivity is increased.

The functions are:

1. *Starts and maintains the arc:* includes striking the arc and maintaining the correct arc length
2. *Feeds the electrode into the arc:* feeding the electrode or cold filler wire into the arc or weld pool
3. *Controls the heat for proper penetration:* involves manipulating the electrode or torch for proper molten weld metal control
4. *Moves the arc along the joint (travels):* provides relative motion at a given velocity along the joint
5. *Guides the arc along the joint:* tracks or follows the joint
6. *Manipulates the torch to direct the arc:* manipulates the electrode or torch to direct the arc in the proper place for bead placement and joint fill
7. *Corrects the arc to overcome deviations:* senses abnormalities and makes changes in welding parameters

In "automatic" welding the welding apparatus is programmed to provide the exact taught motion patterns and the exact preset welding parameters. In many cases

FIGURE 12-1 **Human–machine relationship for arc welding with automation.**

Method of Application / Arc Welding Elements/Function	MA Manual (closed loop)	SA Semiautomatic (closed loop)	ME Machine (closed loop)	AU Automatic (open loop)	AD Automated (closed loop)
					
Starts and maintains the arc	Person	Machine	Machine	Machine	Machine (with sensor)
Feeds the electrode into the arc	Person	Machine	Machine	Machine	Machine
Controls the heat for proper penetration	Person	Person	Machine	Machine	Machine (with sensor)
Moves the arc along the joint (travels)	Person	Person	Machine	Machine	Machine (with sensor)
Guides the arc along the joint	Person	Person	Person	Machine via prearranged path	Machine (with sensor)
Manipulates the torch to direct the arc	Person	Person	Person	Machine	Machine (with sensor)
Corrects the arc to overcome deviations	Person	Person	Person	Does not correct, hence potential weld imperfections	Machine (with sensor)

the weldment is simple and the parts are sufficiently accurate so that changes are not required in the welding conditions or the taught motion pattern. Good-quality welds will result since the inherent tolerance of the welding process will accommodate minor variations. If the joint location or geometry is beyond established variations, a defective weld may result.

An automatic or automated welding system consists of at least the following:

1. *Welding arc:* requires a welding power source and its control, an electrode wire feeder and its control, the welding gun assembly, and necessary interfacing hardware.
2. *Master controller:* controls all functions of the system. It can be the robot controller or a separate controller. It is the overall controller.
3. *Arc motion device:* can be the robot manipulator, a dedicated welding machine, or a standardized welding machine. It may involve several axes.
4. *Work motion device:* can be a standardized device such as a tilt-table positioner, a rotating turntable, or a dedicated fixture. It may involve several axes.
5. *Work holding fixture:* must be customized or dedicated to accommodate the specific weldment to be produced. It may be mounted on the work motion device.
6. *Welding program:* requires the development of the welding procedure and the software to operate the master controller to produce the weldment.
7. *Consumables:* includes the electrode wire or filler metal, the shielding media (normally gas), and possibly a tungsten electrode.

This "automatic-automated" arc welding system is shown in Figure 12-2. Changing the top block from "master control with welding program plus human operation" to "master control with welding program and feedback and adaptive control," and changing the bottom right from human monitoring and supervision to multisensors, changes this from an automatic to an automated welding system.

There are differences in the degree of automation of a welding system. This depends on the number of sensors employed to monitor conditions. Sensors are needed to find the joint, provide root penetration, provide bead

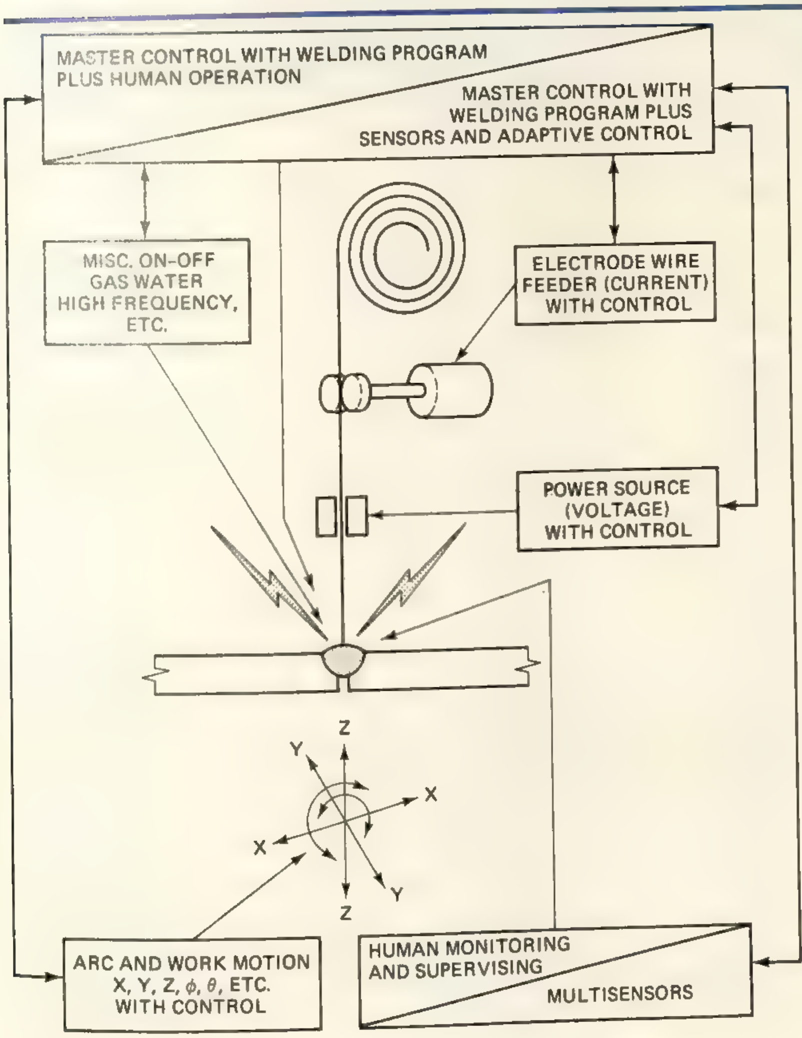


FIGURE 12-2 Automatic or automated arc welding systems.

placement, follow the joint, assure joint fill, and so on. Adaptive control requires sensing devices and computerized circuits that alter the motion and value of a particular parameter in order to compensate and satisfy the new requirements. Many sensing devices will be required to provide total adaptive controlled or automated welding. Sensing devices and adaptive controls are expensive, and at this time only a few "real-time" sensors are perfected for shop production use.

The subject of automated versus automatic welding is in a state of change and the definitions are not all agreed upon and consistent. Automated welding is defined as "welding with equipment that performs the entire welding operation without human observation or intervention. Required adjustments are determined by sensing devices which monitor the arc and feeds information to the control system." The adaptive controller automatically determines changes in process conditions and directs the equipment to take appropriate action to ensure a good-quality weld.

Mechanized welding is a general term that includes machine welding, automatic welding, and automated welding. Mechanized welding is available with different degrees of control, from the simple to the most complex system with full closed loop.

Automated welding will become more widely used. It will be required for large weldments, particularly those requiring multipass welds. However, automated welding will not become widespread until the sensing devices become more sensitive, more rugged, and less expensive.

12-2 ARC MOTION DEVICES

Arc motion devices are required for mechanized welding. The machine moves the arc, torch, and welding head along the joint. The individual or operator performs a supervisory role and may make adjustments to guide the arc, manipulate the torch, and change parameters to overcome deviations. Since the individual is partially removed from the arc area, higher currents and higher travel speeds can be utilized. The fatigue factor is reduced and the operator factor or duty cycle is increased. Productivity is increased, with a resulting reduction of welding costs.

Arc motion devices fit into five categories:

1. Manipulator (boom and mast assembly)
2. Side beam carriages
3. Gantry or straddle carriages
4. Tractors for flat-position welding
5. Carriages for all-position welding

The arc motion devices carry the welding head and torch and provide travel or motion relative to the part being welded. They are used for all the continuous wire processes, gas metal arc, flux-cored arc and submerged arc welding, and also for gas tungsten arc and plasma arc welding. The motion device must be matched to the welding process. Gas tungsten and plasma arc welding require more accurate travel and speed regulation. This must be specified since tighter tolerances are used in manufacturing and the equipment will be more expensive.

Manipulator

A welding manipulator consists of a vertical mast and a horizontal boom which carries the welding head. They are sometimes referred to as boom and mast or column and boom positioners. Figure 12-3 shows a welding manipulator being used for submerged arc welding the circumferential joint of a large tank. Manipulators are specified by two dimensions—the maximum height under the arc from the floor and the maximum reach of the arc from the mast. The manipulator can be designated as a 6 × 6, which means that the height (z) weldable is 6 ft high and it can weld at a distance (y) 6 ft from the face of the mast. Other manipulators range from 4 × 4 to 12 × 12 and larger. A more detailed way of specifying manipulators is shown in Figure 12-4. Many companies supply this type of equipment. Manufacturers provide similar data for their equipment plus the maximum weight that can be carried on the end of the boom and the maximum deflection.

There are many variations of manipulators. The assembly may be mounted on a carriage which travels on rails secured to the shop floor. The welding power source is usually mounted on the carriage. The length of travel can be unlimited; thus the same welding manipulator can be used for different weldments by moving from one workstation to another. In this example the welding operator sits on a seat attached to the boom and the controls are at the operator's station. This is a heavy-duty model, to support the weight of the welding operator, electrode wire supply, flux supply, and welding head. Manipulators usually have power for moving the boom up and down on the column. The boom may extend and move through the vertical adjusting assembly as shown, or the welding carriage head may move by power in and out along the boom to provide transverse motion. In some units the mast may rotate, but not with power. In selecting and specifying a welding manipulator it is important to determine the weight to be carried on the end of the boom and how much deflection can be allowed. The welding torch should move smoothly at travel speed rates compatible with the welding process. The manipulator carriage must also move smoothly at the same speeds. Carriages should have high-speed return. Figure 12-5 shows a precision manipulator for gas tungsten arc welding. A precision manipulator, when specified, would have a "tracking" tolerance of 0.0015 in. per foot of reach runout. Standard manipulators would have a tolerance of $\frac{1}{32}$ in. per foot of reach runout. The quality of the

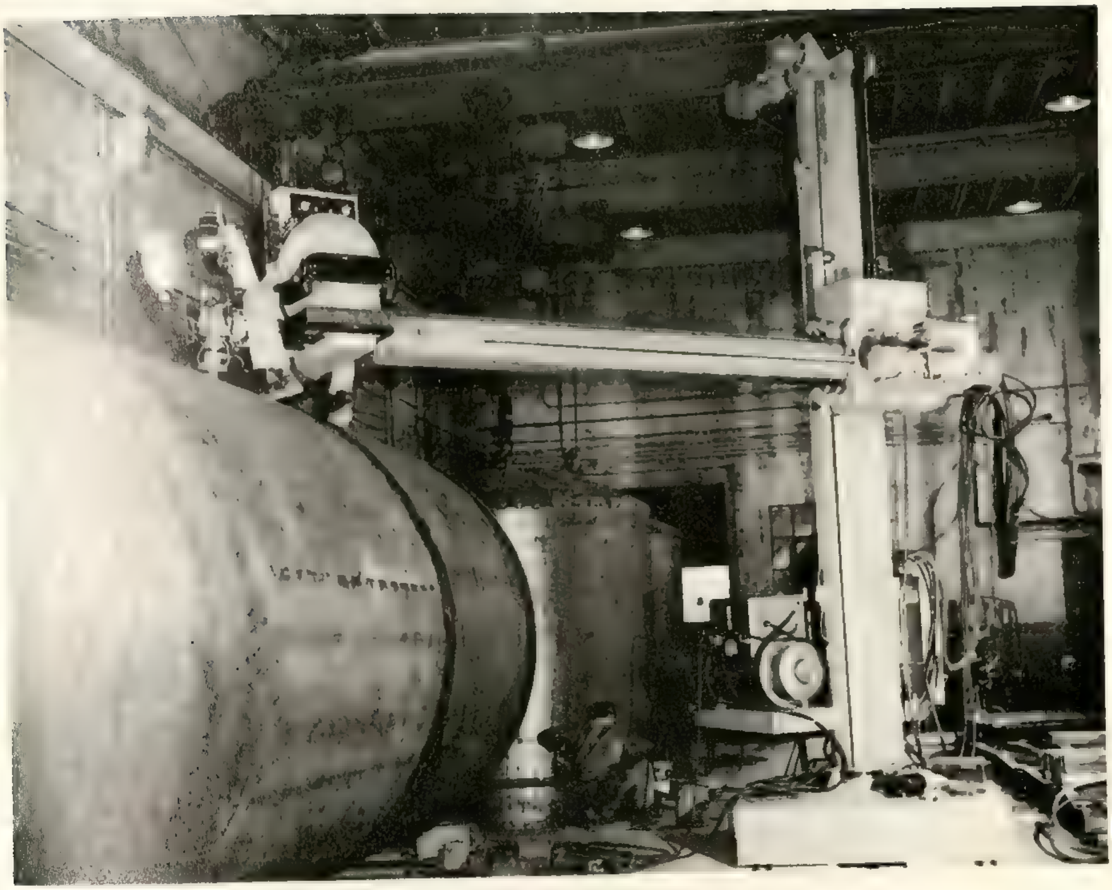
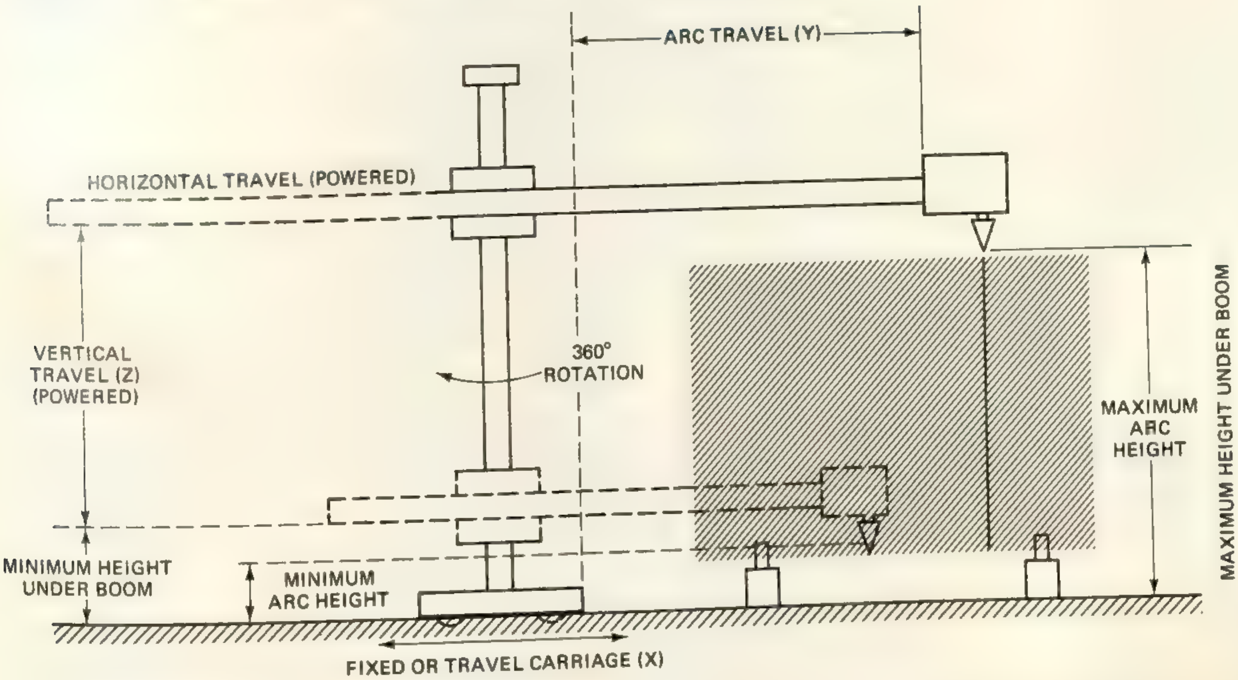


FIGURE 12-3 Welding manipulator (SAW).

FIGURE 12-4 Manipulator dimensions for specifying.



hardware and adjusting devices largely determines the precision of the total machine.

Manipulators are one of the most versatile pieces of welding equipment available. They can be used for longitudinal straight-line welds, transverse straight-line welds, and with special controls a combination of these; also for circular welds when fixed in position with a rotating device.

Side Beam Carriage

The side beam carriage is less versatile and less expensive than the boom and mast manipulator. The side beam carriage performs straight-line welds with longitudinal travel of the welding head. A side beam carriage using the flux-cored arc welding process is shown in Figure 12-6. In this case the carriage is mounted on an I-beam modified with bars to provide for powered travel. Side beam carriages are available with high-precision motion, depending on the accuracy used in the manufacture of the beam and the speed regulation of the travel drive system. Figure 12-7 shows a precision side beam carriage for gas tungsten arc welding. The carriage will carry the welding head, wire supply, and so on, and the controls for the operator. The welding head on the carriage can be adjusted for different heights and for in-and-out variations. The welding arc is supervised by the welding operator, who makes adjustments to follow joints that are not in perfect alignment. The travel speed of the side

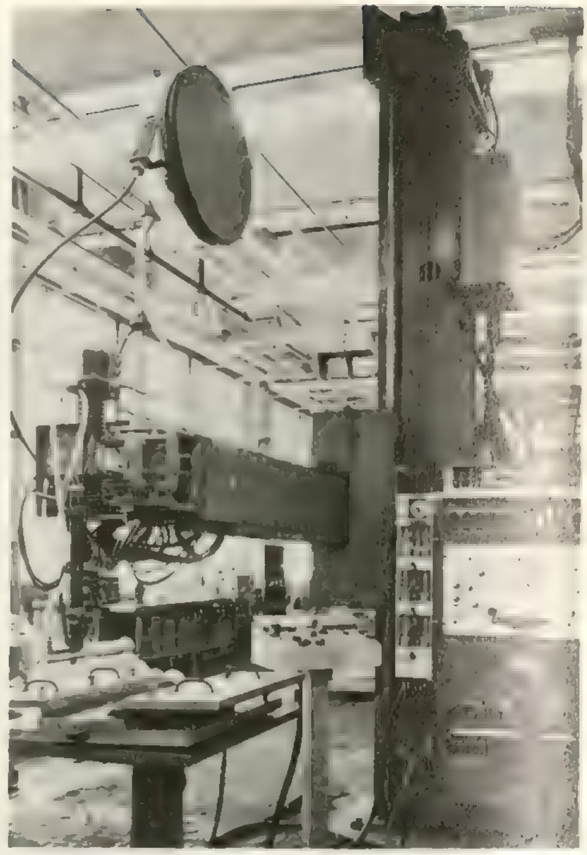


FIGURE 12-5 Precision manipulator (GTAW)

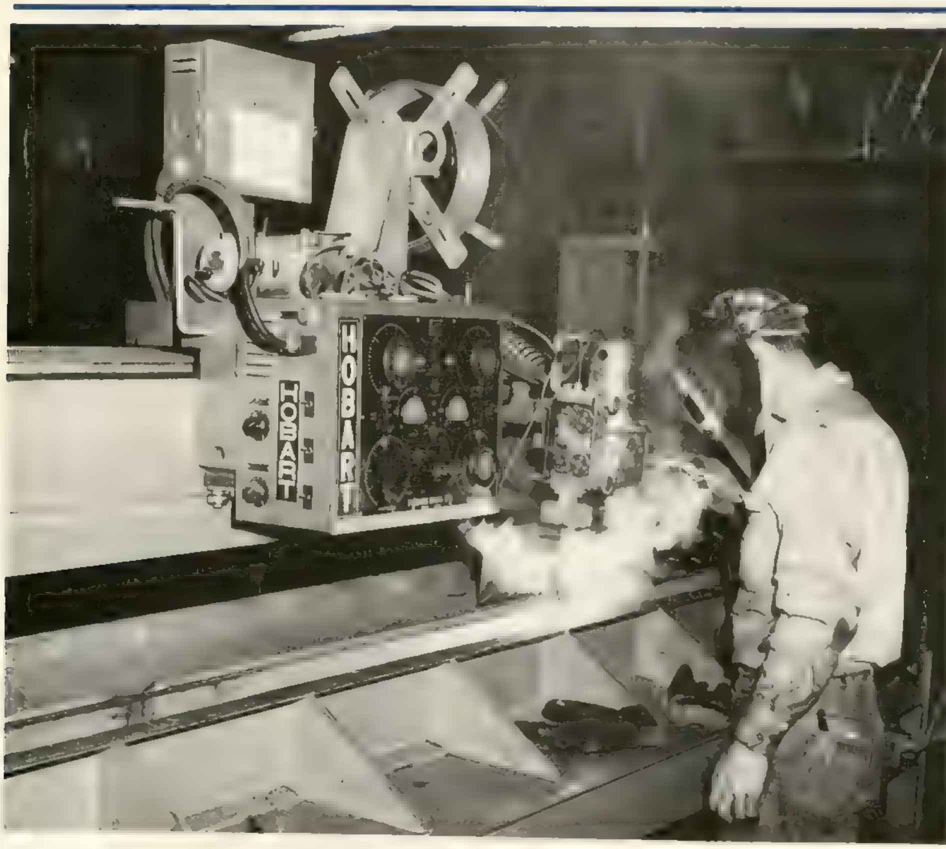


FIGURE 12-6 Side beam carriage.

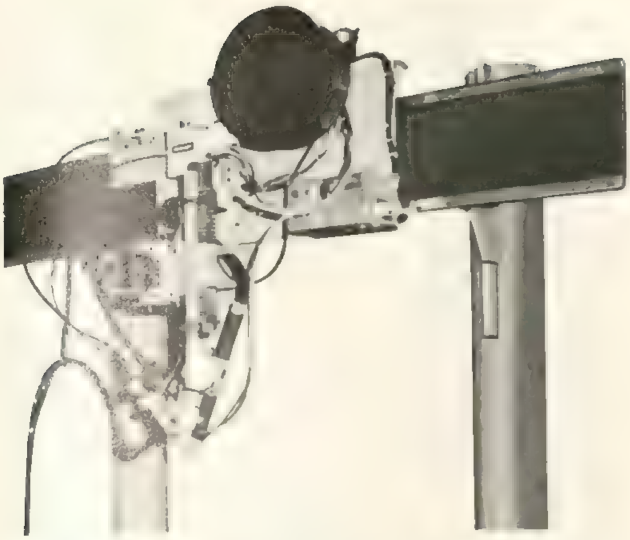


FIGURE 12-7 Precision side beam carriage.

beam carriage is adjustable to accommodate different welding procedures and processes. Rapid return speed may be available. A side beam carriage can be teamed up with a work-holding device for making different parts that require straight-line welds.

Gantry Welding Machine

Gantry arc welding machines are arc motion devices that provide one or two axes of motion. The gantry consists of a horizontal beam supported at each end by a powered carriage (Figure 12-8). The gantry structure straddles the work to be welded and the carriages run on two parallel rails secured to the floor. This provides the X or longitudinal motion and can be quite long. The length of the gantry bridge determines the width of the parts that can be welded. The torch or torches are mounted on carriages that move along the gantry beam. This provides the Y or transverse motion. The travel speed of the carriages must be smooth and match the welding speed of the welding process. However, rapid travel should be available for returning. It should go in either direction at welding speed and at high speed. The one or more welding heads on the gantry bridge will have power travel or will have adjusting devices to locate the head over the weld seam. Usually, a maximum of two torches are provided for transverse motion. The X and Y motions are not normally operated simultaneously.

Welding Tractor

A welding tractor is an inexpensive way of providing arc motion. Tractors of this type are commonly used for mechanized flame cutting. Some tractors ride on the material being welded, while others ride on special tracks. The tractor should have sufficient stability to carry the welding head, the electrode wire supply, flux if used, and the welding controls. The welding tractor shown in Figure 12-9 rides on a track and has adjustment so that the head will follow the weld joint. This type of equipment is extremely popular in shipyards and in plate-fabricating shops. The travel speed of the tractor must be closely regulated and smooth, and related to the welding process. It must have sufficient power to drag cables. A more specialized tractor is shown in Figure 12-10. This unit carries two heads and straddles a stiffener that is being double-fillet welded to a plate.

All-Position Welding Carriage

There are many requirements for mechanized vertical or horizontal position welding. A tractor that utilizes a special track that holds the tractor is used. Figure 12-11

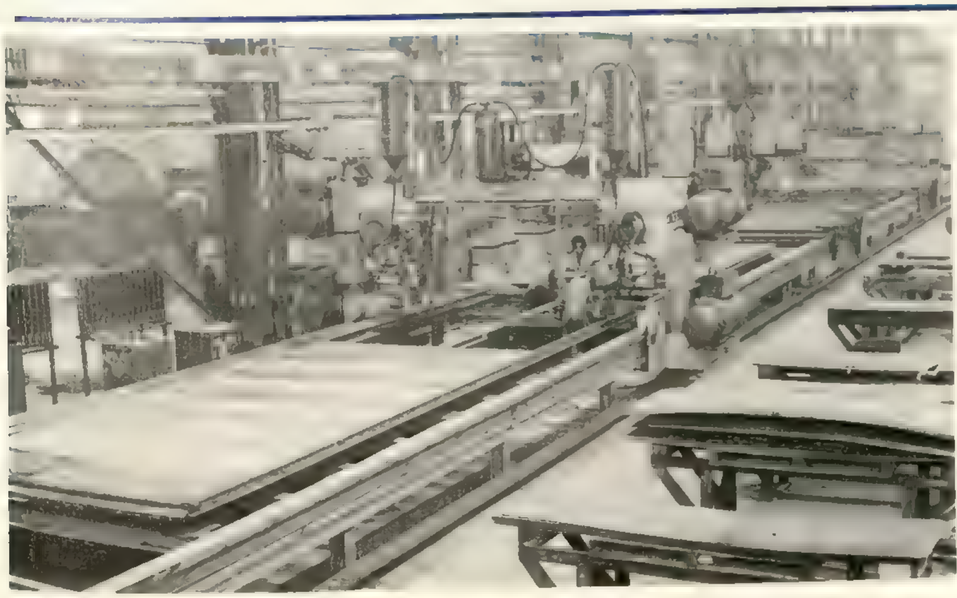


FIGURE 12-8 Gantry welding machine with two heads.

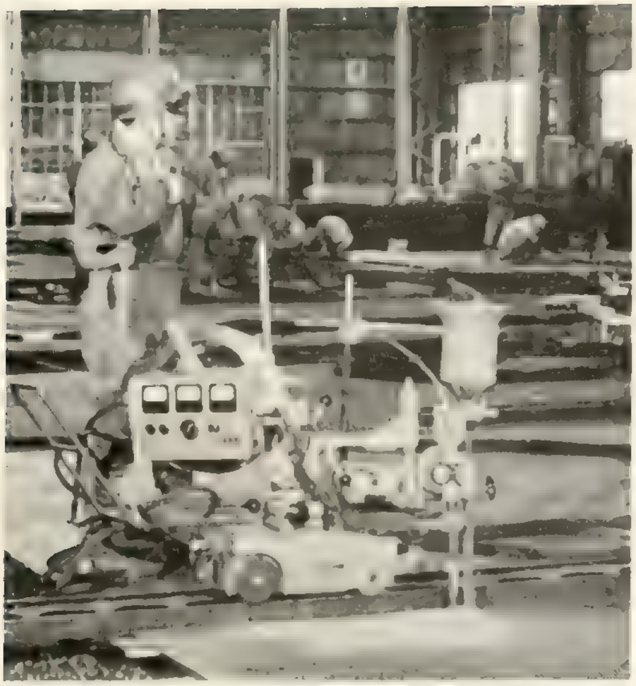


FIGURE 12-9 Welding tractor (SAW).

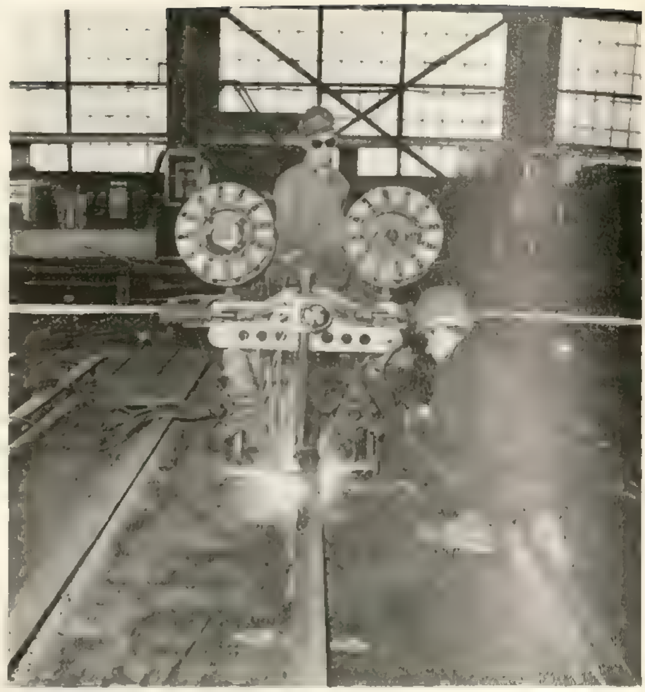
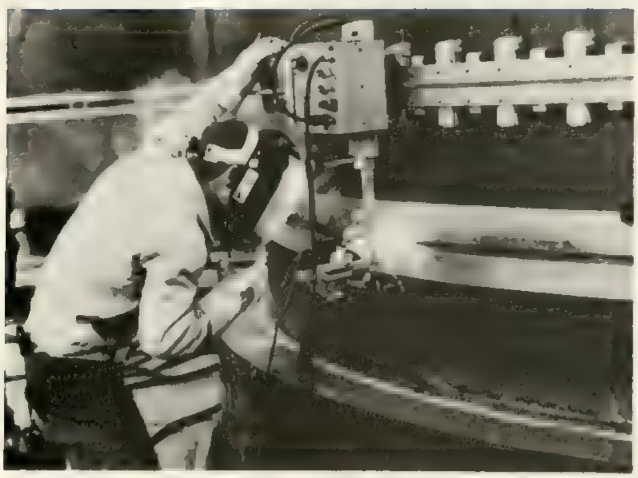


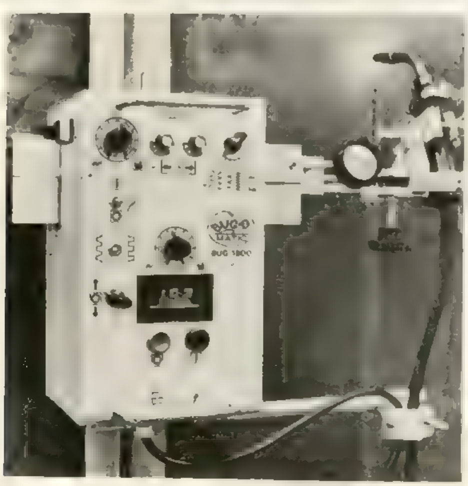
FIGURE 12-10 Stiffener welding tractor (two FCAW axis).

FIGURE 12-11 All-position welding tractor; (a) horizontal, (b) vertical, (c) overhead.



(a)

(b)



(c)

shows an all-position welding carriage that carries the welding gun. The gun is connected to the wire feeder by means of the standard cable assembly. In this case an oscillator is employed to provide lateral arc motion. This type of welding carriage can be used in the flat, vertical, horizontal, or overhead positions. Adjustments can be made to align the torch to the joint and for maintaining this alignment. The track can be attached to the work with magnets or vacuum cups.

A special type of carriage is used for welding the horizontal girth welds on large storage tanks (Figure 12-12). The carriage may straddle the top course of plates and make welds simultaneously on the inside and the outside of the tank shell. Other carriages are designed for vertical welding that carry the welding head and sometimes the controls and the welding operator. They are used for the vertical joints of storage tanks and ships. A special carriage known as a skate welder is designed to follow irregular joint contours inside complex structures. Skate welder travel units are extremely compact and carry a miniaturized wire feeder or only a torch. Skate welders are used for welding inside aircraft assemblies, for example.

FIGURE 12-12 Tank construction welding carriage.

12-3 WORK MOTION DEVICES

A welding work motion device, commonly called a welding positioner, is a device that holds and moves a weldment to the desired location and angle for welding. The axis of the welds of a complex weldment are in many different angles and directions. By means of a positioner the weldment can be moved to put each weld in its most advantageous welding position. For manual or semiautomatic operation this is the flat or down-hand position, since flat position is the most productive. Flat-position welding is faster because larger electrodes at higher welding current can be used and the weld can usually be made with fewer passes. It also has a higher quality level and will have a better appearance. Another reason is the improvement in the operator factor; a welder welding in the flat position will be more comfortable, will have less fatigue, and will have a higher percentage of arc time.

There are a number of negative aspects to weld positioning. Positioning equipment is relatively expensive, and to be cost-effective the savings of flat welding must pay back quickly. The weldment must be firmly attached to the positioner for safety reasons. The time required for loading and unloading the positioner must be considered in cost calculations justifying positioners.

The primary considerations for selecting a welding positioner are the size, shape, and weight of the weldment and the size, type, and quantity of welds.[1] In addition, consideration must be given to the lot size of production and the number of welders or arcs working simultaneously.

The type of production is important. For example, if like weldments are to be produced simultaneously, there must be a sufficient number of positioners so that all the weldments can be welded in the shortest possible cycle time. If there is only one positioner and each weldment requires a day on the positioner, it would take a week to produce five weldments. If there were five positioners, all five weldments could be welded simultaneously in one day. The cycle time versus the lot size of production must be considered carefully. In addition, there is the problem of accessibility for welding. The side attached to the positioner table may not be accessible for welding, and this requires relocating the weldment on the positioner. Most positioners hold the weldment above the floor so that ladders or scaffolding are used to bring the welders close to the work. This extra equipment must be considered in the overall capital cost.

Four types of welding positioners are used for manual and mechanized welding, and one type is used for manual or semiautomatic welding only.

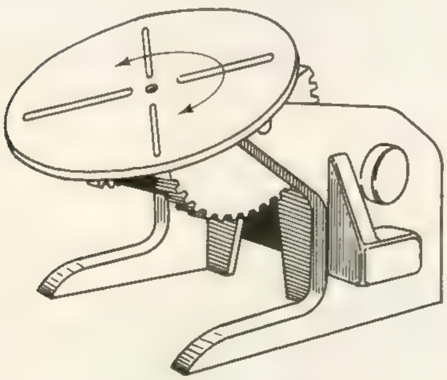
1. Universal or tilt-table positioner
2. Turning rolls
3. Head and tail stock positioners
4. Balanced positioners (used only for manual welding)

Additionally, there are specialized positioners designed to be used with robots. There can be combinations of the different types and they can be very small to very large in size and capacity.

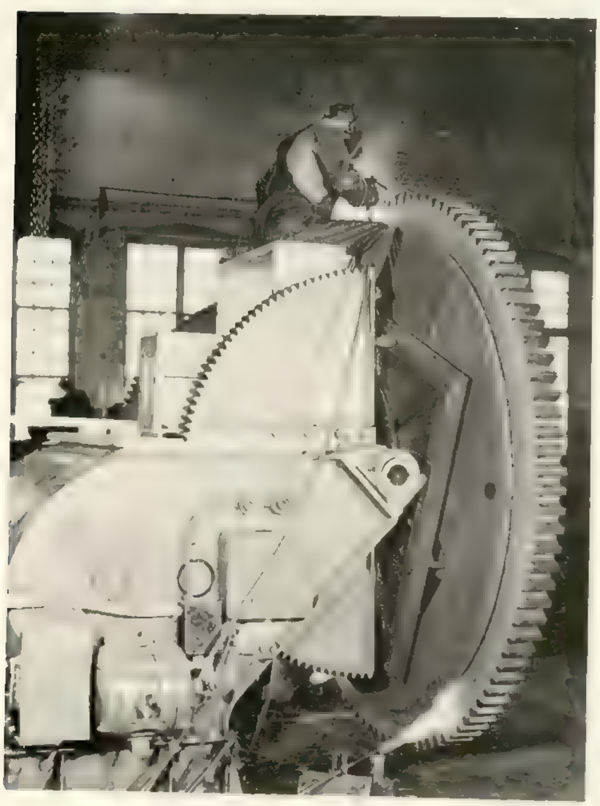
Universal or Tilt-Top Positioner

The universal tilt-table positioners are the most popular. An example is shown in Figure 12-13. Powered positioners are available for handling weldments weighing from 100 lb (45.36 kg), known as bench positioners, to 150 tons (135 mg) or more for heavy-duty positioners. The principle of operation is a table that can be tilted from horizontal to the vertical position and beyond the vertical position by power. The table rotates about its center by power. The size of the table, which may be round or square, depends on the capacity of the positioners. Tables range from 12 in. in diameter up through 10 ft (3.05 m). Positioners must be securely anchored to

FIGURE 12-13 **Table-type welding positioner.**



UNIVERSAL GEAR-DRIVEN POSITIONER



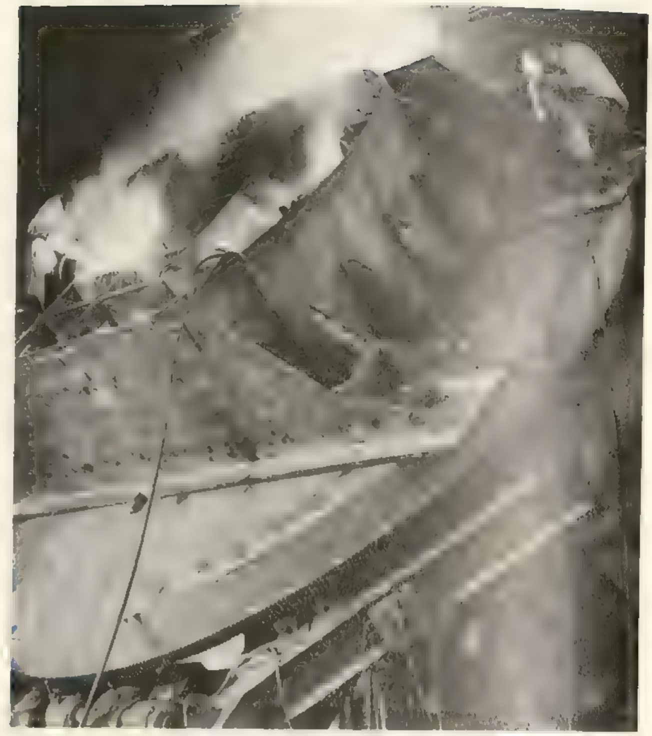


FIGURE 12-14 **Large weldment on bigger positioner.**

the floor to avoid tipping over due to the strains imposed by heavy loads. The rotational and tilting speed of the table pertain to the size of the positioner. A much larger tabletop positioner is shown in Figure 12-14.

When selecting a positioner, two factors must be considered in specifying its size. A positioner is rated based on its ability to provide specific tilting and rotational torques. For tilting this is expressed in inch-pounds, which is the concentrated weight or center of gravity of the weldment times the distance from the face of the table when in the vertical position. This is shown in Figure 12-15 as weight W in pounds times distance D in inches. S is the inherent overhang designed into the machine. It is impossible for the centerline of gravity to be at the table face.

For rotation the rated capacity is the product of the weight in pounds times the distance in inches from the center of gravity of the load to the centerline of table rotation. This is the distance in inches of eccentricity, shown by E in the figure. Each capacity is determined independently by the design of the yoke and frame members of positioner. Positioner manufacturers provide load capacity charts that show safe operating limits based on the weight of the load, the distance from the face of the table, and the eccentricity of the load.

It is extremely important to know the location of the center of gravity of weldments that are placed on positioners. This can be calculated accurately from the engineering drawing. However, its location can be approximated, in the shop, by balancing the weldment

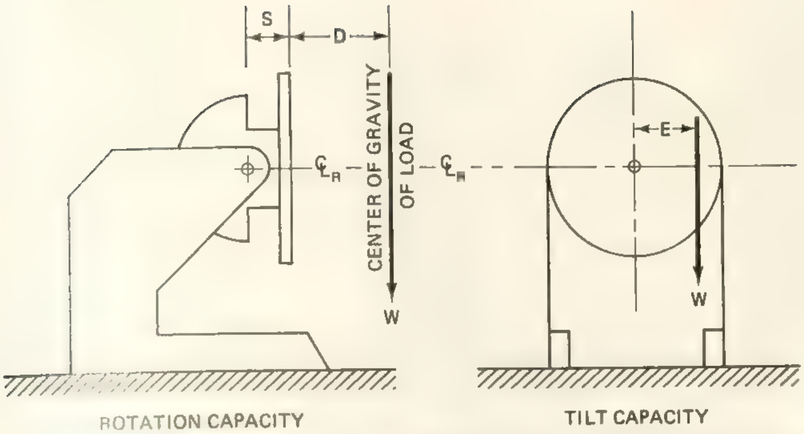


FIGURE 12-15 Center of gravity of load and location.

on an inverted angle iron in all three planes. Even with this information it is difficult to align the center of gravity of the weldment precisely with the center of rotation of the table.

The weldment must be very firmly attached to the positioner table. Most positioner tables have slots for bolts for this purpose. In some cases fixtures may be attached to the positioner table. Whenever fixtures are employed, the weight of the fixture must be included in establishing the total weight of the load.

Rotational speeds are important since positioners are often used for rotating parts under a fixed welding head. The travel or circumferential speed must be within the parameters of the welding procedure. Manufacturers provide specifications showing tilt and rotational speeds.

Positioners must be well manufactured, with appropriate bearings and motors, so that travel speed is smooth and steady. A variation of the universal tilt-table positioner utilizes mechanical or hydraulic elevating mechanisms for raising or lowering the table. Another variation is the horizontal turntable, which is similar to the conventional turntable but without the tilt feature.

Turning Rolls

Turning rolls are ideally suited for cylindrical parts such as tanks. Turning rolls come in many sizes and ratings, based on the size and weight of the work to be rotated. These range in size of rolls that will turn loads of from 1 ton up through 250 tons. Usually, powered set of rolls and idler sets are used together. Figure 12-16 shows the normal arrangement for turning rolls with a very large heavy cylindrical load. For extremely heavy loads or long cylindrical members, additional sets of idler rolls can be used. For flexibility of operations the sets of rolls can be placed on tracks so that they can be adjusted for long or short cylindrical weldments. The center-to-center spacing of the turning rolls shown by the figure relates to the diameter of the cylindrical part being rotated. Angle *A* should be 45°. Double sets of rollers are used for heavy loads. They distribute the load over more area of the rolls and the weldment. The surface of the turning rolls can be metal or composition. The composition rollers do not have as high a load capacity and should not be used when high-temperature preheating is used. The size of the drive motor is related to the size and weight capacity of the rolls. The off-center weight of the weldment must be considered. It also has an effect on the rotational speed of the weldment. The rotational speed of the rolls must be selected so that the speed of the weld will be compatible with the travel speed of the welding procedure. The speed of rotation must be smooth and steady.

Turning rolls must be accurately aligned or else the cylindrical weldment will tend to move sideways during rotation. This is not acceptable when making circumferential welds.

Rolls are usually used with cylindrical parts; however, by the use of round fixtures or rings, noncylindrical parts can be rotated with conventional rolls. The rings are made in halves which are clamped around the part to be rotated. With ring fixtures rectangular, square or unusual-shaped weldments can be rotated for ease of welding (Figure 12-17). Note the adjustment screws, used so that different-sized rectangular weldments can be accommodated. This technique has been used for rotating small ships, for example. Smaller turning rolls can be mounted on head and tail stock positioners for special applications.

Head and Tail Stock Positioners

Head and tail stock positioners (Figure 12-18) perform much the same function as turning rolls. They are similar to tilt-table positioners. A tilt-table positioner can be used for the head stock or powered member. The tilting device is deactivated so that only the power rotation is employed. Head stock positioners normally do not have the tilt feature. The capacity of head and tail stock positioners is similar to that of tilt-table positioners and ranges from 5 tons up to 50 tons. Since there are two units, the overhang weight problem is less important. The eccentricity weight must be considered. Head and tail stock

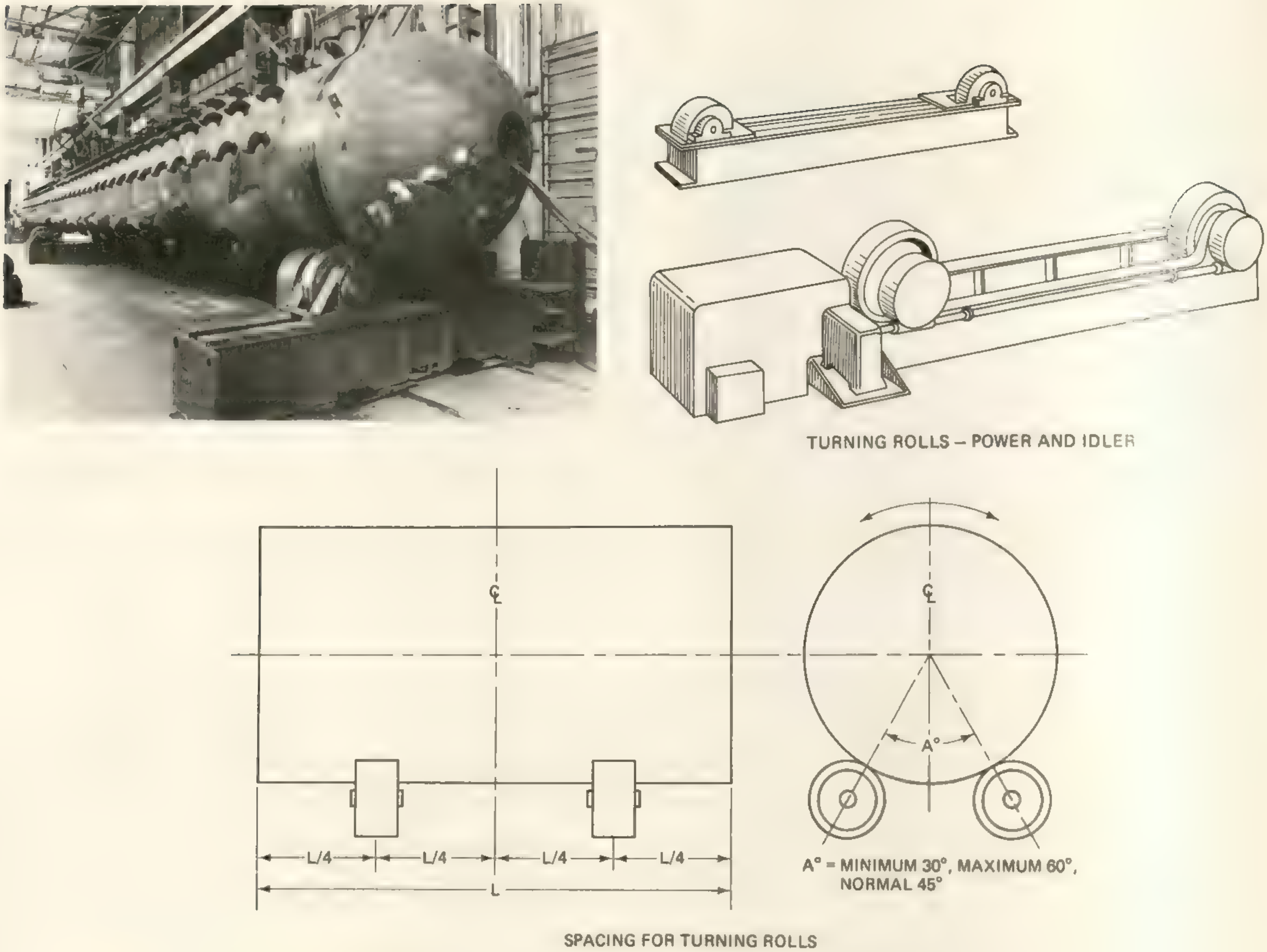


FIGURE 12-16 Turning rolls.

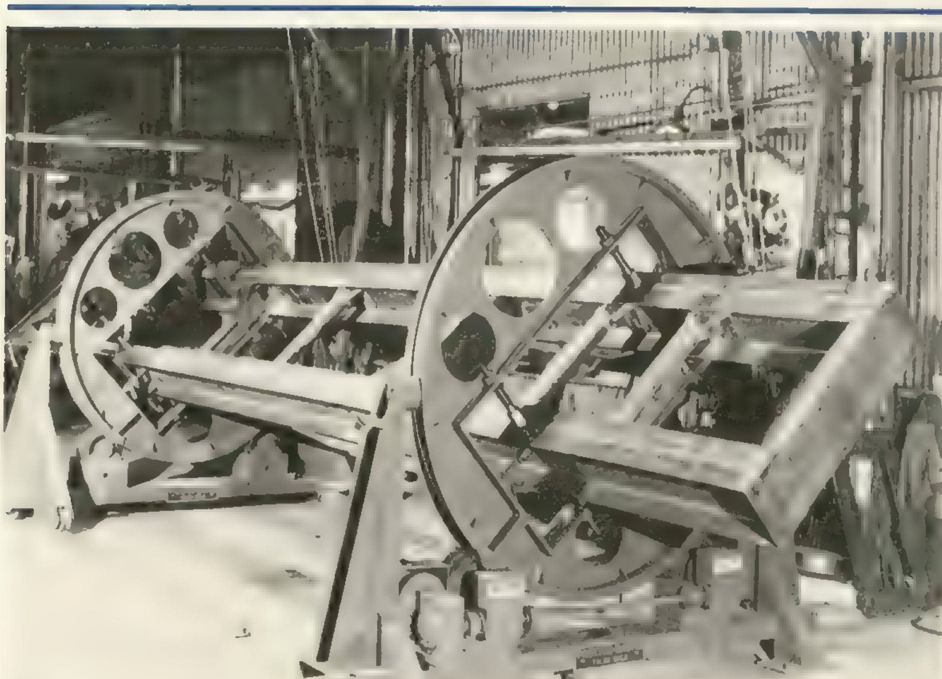
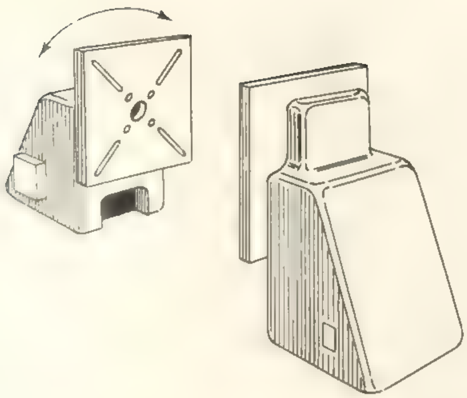


FIGURE 12-17 Ring fixtures holding rectangular parts on turning rolls



HEAD AND TAIL STOCK POSITIONER

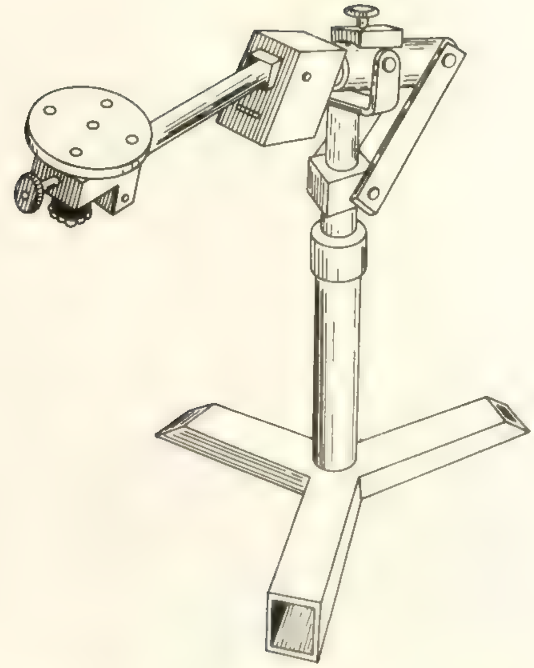


FIGURE 12-18 Head stock/tail stock positioner.

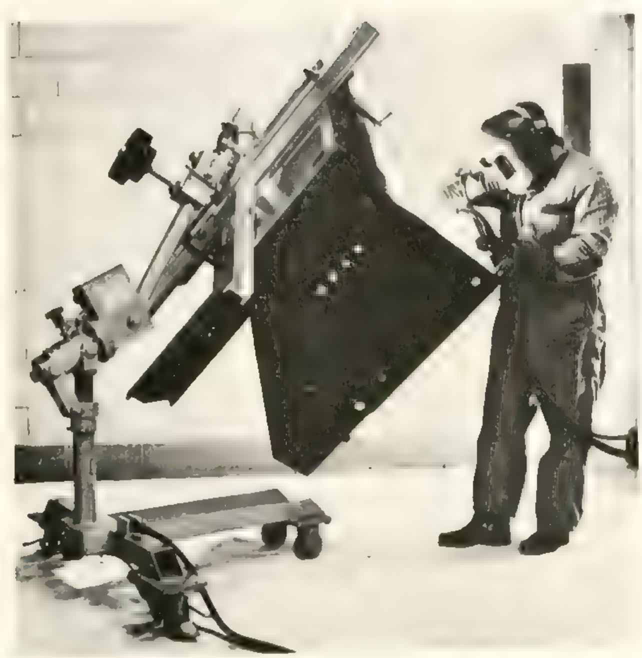


FIGURE 12-19 Balanced positioner.

positioners are used when long, irregular-shaped weldments are produced. Head and tail stock positioners are commonly used in railroad car building shops to rotate cars during the welding operation.

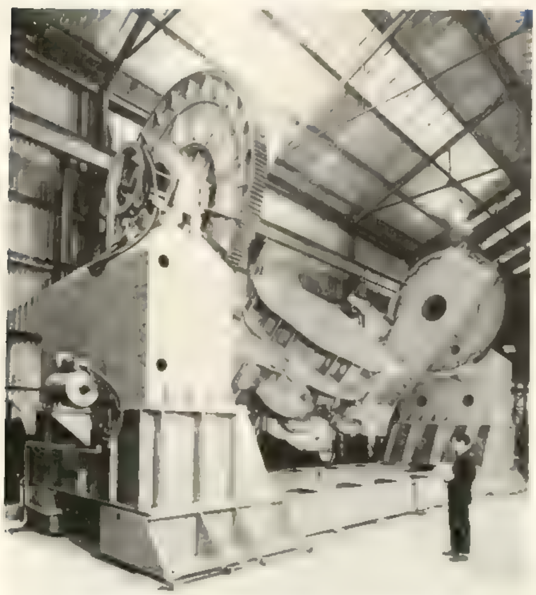
Universal Balanced Positioners

These positioners are relatively small compared to most powered tilt-table positioners. They are balanced and do not contain power; however, power rotation of the table is available. The universal balanced positioner is shown in Figure 12-19. The principle of this type of positioner is to determine accurately the center of gravity of the weldment and adjust the angles of the arms of the positioner so that the center of gravity is in line with the main axis of rotation of the arm and in line with the axis of rotation of the table. When the weldment is properly located and balanced on the positioner, it can be moved very easily to put it in any position required for welding. This type of unit is extremely popular for weldments that are too heavy to lift manually but do not require powered tilt-table positioners. When sufficient volume is to be produced, fixtures can be attached to the positioner so that when the parts are loaded they are accurately located at

the balance points. These positioners come in sizes ranging from 100 to 2000 lb and have proven to be very efficient for smaller weldments. They are normally used with manual or semiautomatic welding.

There are many other types of positioners; some are made for special applications. One type, known as the cradle or drop center positioner, is shown in Figure 12-20. This type has two axes of rotation, but the overhang problem is less. They can be made in different sizes and weight capacities.

FIGURE 12-20 Drop center positioner.



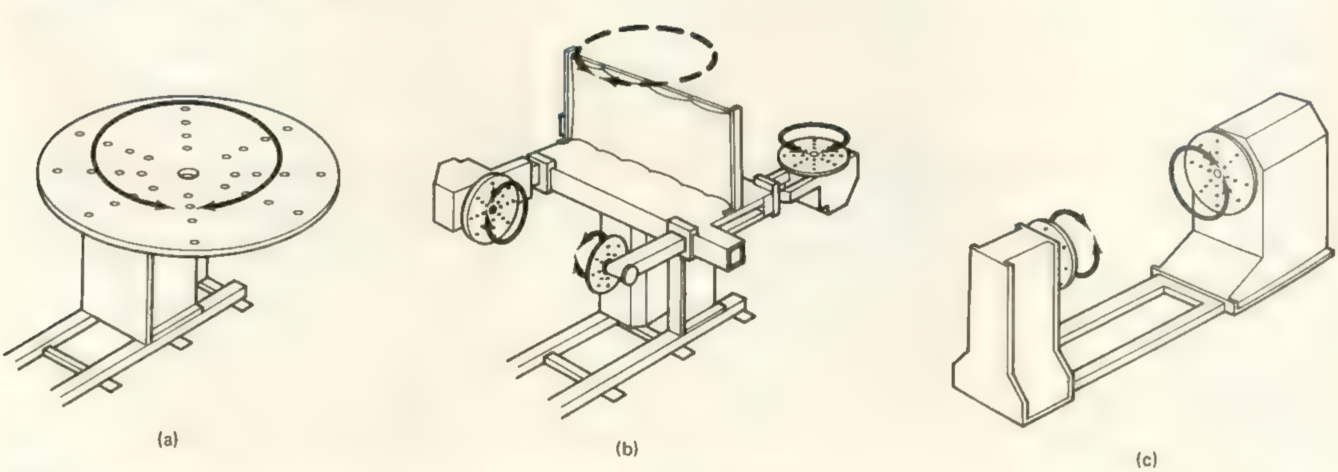
Robotic Arc Welding Positioners

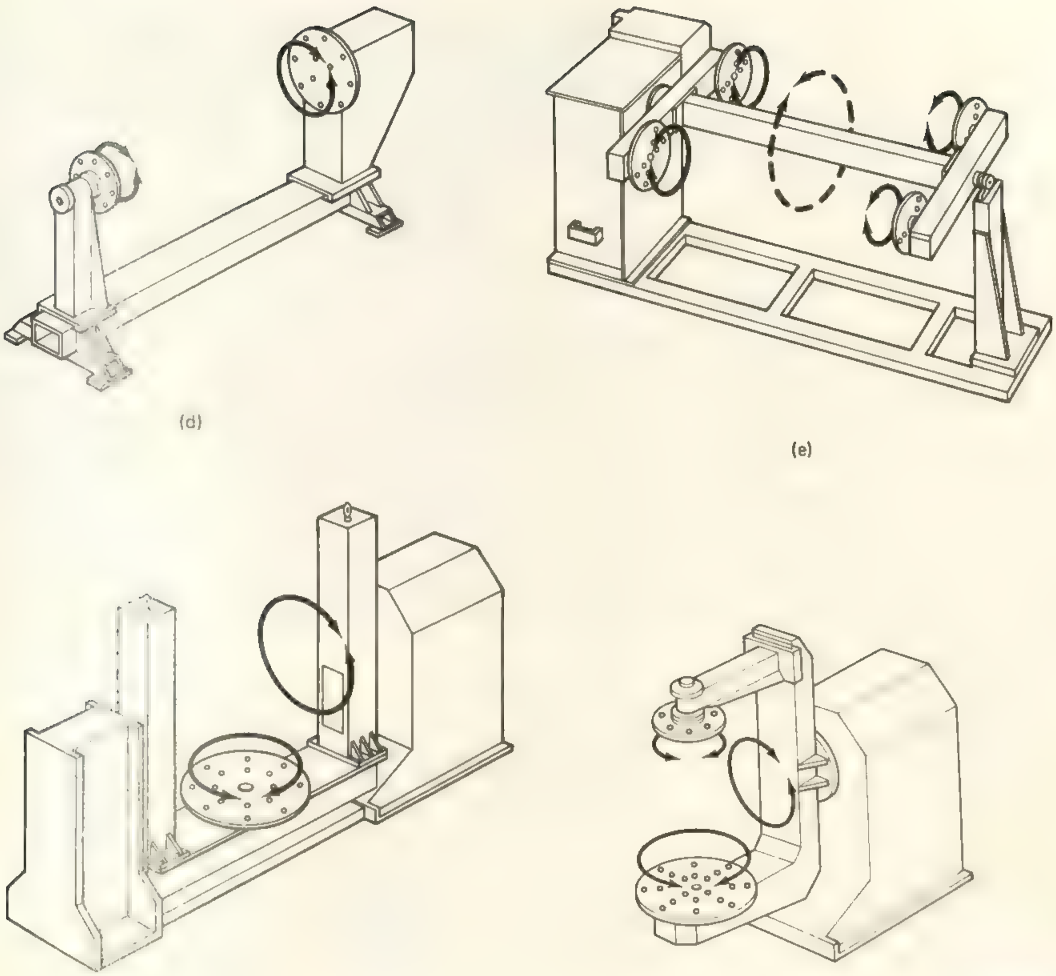
Specialized positioners are used to improve the versatility and to extend the range of robotic arc welding systems.[2] The usable portion of a robot work envelope can be limited because the welding torch mounting method does not allow the torch to reach the joint properly. The lead and lag angles of the torch, which are controlled by the robot's wrist movements, reduce the distances that the torch tip can be extended. Thus the robot working range is limited since it is normally anchored at a fixed location. Special positioners eliminate some of these limitations by making the workpiece more accessible to the robot welding torch. They also provide additional axes of motion to the system. A variety of positioners are used with robots, including single- and dual-station types and the universal tilt table unit manufactured to tighter tolerances. Backlash is normally +0.001 in. per inch (0.0025 mm per 25 mm). The positioners used with robots must be more accurate than required for manual or semiautomatic welding. In addition, the robot positioner controls must be compatible and controllable by the robot controller in order to have simultaneous coordinated motion of several axes while welding.

The following is a brief description of some of the more popular robot positioners which are shown in Figure 12-21. The double-ended or twin-worktable indexing positioner, also called a "turnaround," is very popular. This is a dual-station unit for small or medium-size parts. While welding takes place at one station, the other is being loaded or unloaded. It can have three axes of rotation at each side, and each side does not need to be the same. An example is shown by Figure 12-21b. These units do not normally have coordinated motion.

Single-axis rotational-type positioners that provide coordinated motion are shown in Figure 12-21a, c, and d. Simultaneous coordinated motion is obtained by the combination controller. The axis of motion can be vertical or horizontal. The "turn stock" positioner is used for two fixtures or long, slender weldments. Both sides have rotation, which can be with eight locked positions or with coordinated motion. This is a dual-station positioner with three axes of rotation. An example is shown in Figure 12-21e.

FIGURE 12-21 Robot positioners.





(d) (e) (f) (g)

FIGURE 12-21 (*cont.*).

FIGURE 12-22 Shuttle carriage.

Another positioner, known as the drop center type, is called a "turnover" unit (Figure 12-21f). This unit has two axes of motion. Positioner motion is locked at specific points for welding.

A different type of positioner, also known as a "turnover" unit, is shown in Figure 12-21g. This unit has two axes of rotation and is designed for heavier loads. Positioner motion is locked at specific points for welding.

An item that expands the range of a robot is the shuttle carriage (Figure 12-22). This has a travel range of 6 or 12 ft. The work positioner can be mounted on the carriage or the robot can be mounted on the carriage, enabling it to weld at two workstations alternately. It could be considered an arc motion device. Other special robot positioners are available for special applications.

12-4 STANDARDIZED AUTOMATIC ARC WELDING MACHINES

Standardized automatic arc welding machines are used for producing certain welded products or for making certain types of welds. They are considered standardized

since they are adjustable to accommodate similar products of different sizes with different material thicknesses. They are essentially machine tools for making specific items. They can make longitudinal seam welds on tanks, the weld joining of heads to the shell of a tank, the weld attaching small bosses or spuds to sheets, the welds to fabricate structural beams, pipe welds, and so on. They can be maintenance welding machines for building up tractor rollers, track pads, dipper teeth, and so on.

These machines are usually a combination of an arc motion device and a work motion device designed to work together to weld a family of products. Single or multiple arcs are involved and either continuous electrode welding processes or arc heat welding processes can be utilized. Motion is relatively simple, usually with one axis. Work-holding devices are often involved and may be customized for specific weldments. Many of these standardized machines have complex controls which are programmable to reduce the time involved in setup. The operator only loads and unloads these machines for maximum productivity.

Standardized automatic arc welding machines can be categorized as follows.

- Seamers, external and internal
- Tank head welders
- Welding lathes or circumferential welders
- Pipe and tube orbital welding systems
- Spud welders or rotating head welders
- Beam fabricators
- Strip welders
- Rotary buildup welders
- Rotary longitudinal welders

Machines of these types are available in different sizes with different configurations from numerous manufacturers. Users sometimes build their own standardized machines using commercially available components. Many companies sell matched components for this purpose. Following is a brief discussion of some of the more popular standardized automatic arc welding machines.

The most popular standardized machine is the external seamer (Figure 12-23). This machine utilizes a beam and carriage positioned over a hold-down fixture with a backup. It can be adjusted for different diameters and lengths of tank shells of different material thickness. Seamers use many of the arc welding processes and can be quickly adjusted for different-size shells of different metal thicknesses. The seamer may be adjustable for non-flat-position welding. Welding on an incline downhill improves seam weld productivity. Internal seamers are constructed differently and are used for making the inside weld. An example is shown in Figure 12-24.

A companion piece to the tank seamer is a tank head welding machine. These are sometimes called weld

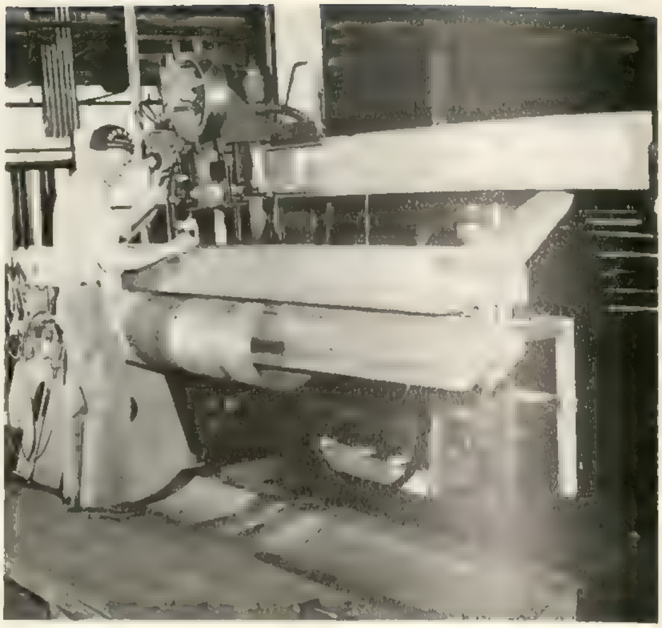
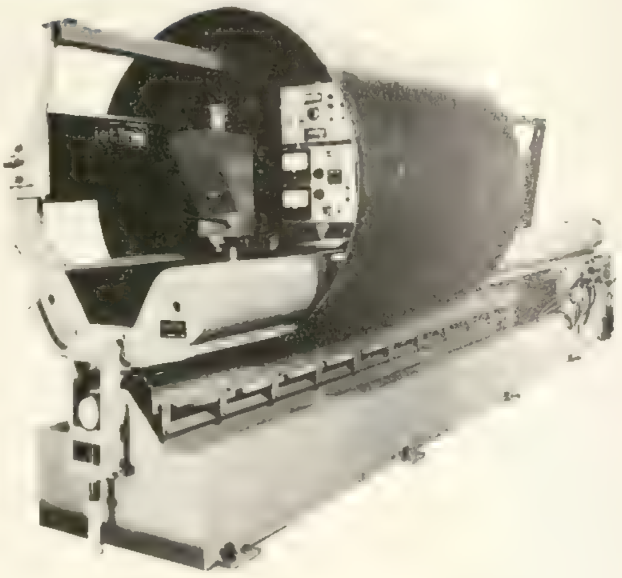


FIGURE 12-23 External seamer.

FIGURE 12-24 Internal seamer.



lathes or circumferential welders. This machine will rotate the tank assembly under two welding heads and will make two cylindrical welds simultaneously, joining the heads to the shell (Figure 12-25). They can be used for different sizes, lengths, diameters, and material thickness. They are commonly used for making LNG tanks, hot water tanks, expansion tanks, and so on.

Another standardized unit is the automatic welding machine for making wide-flange beams. There are two types, one that travels along the beam (Figure 12-26), and another type that pulls the three plates making the beam through the machine. In either case two welds are made

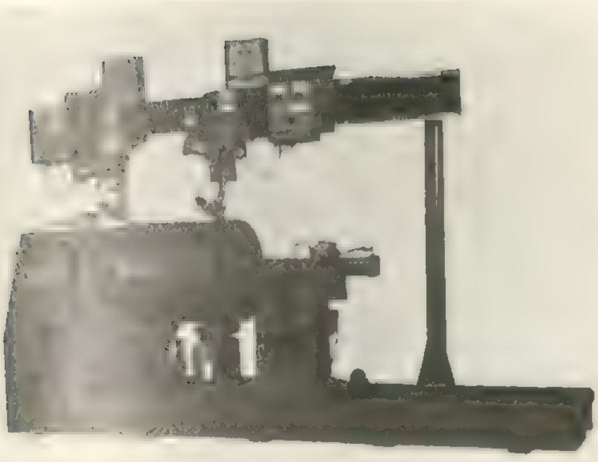
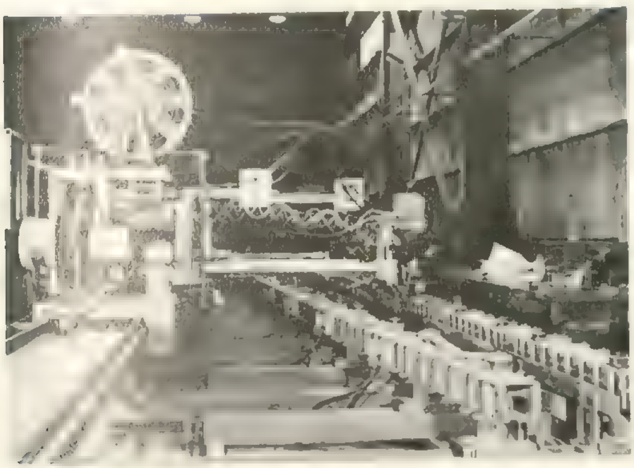


FIGURE 12-25 Circumferential welder-weld lath.

FIGURE 12-26 Traveling I-beam welding machine.



simultaneously, the assembly is turned over, and the other two welds are made. They are adjustable for making different-size beams from different plate thicknesses. These machines are becoming more popular as fabricated beams replace hot-rolled beams.

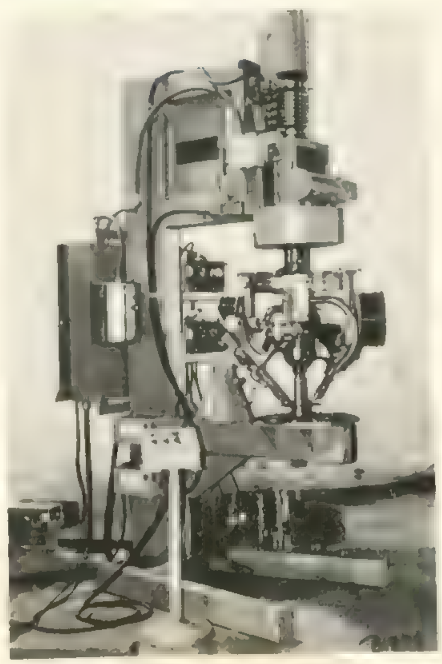
Another standardized welding machine is known as the spud welder. It is also called a boss welder, stub welder, or a rotating head welder. This is a machine that rotates a welding head or sometimes two heads around a relatively small diameter part such as the spud of a tank. The head rotates the arc around the periphery of the part and makes a fillet weld joining it to a plate. These machines are used in the tank industry and can be used for welding small-diameter parts to flat or curved plates. When curved plates are involved, cams are used to follow the irregular seam. They are quickly adjustable for different sizes of spuds and they may clamp the parts as well as make the welds. A typical spud welder is shown in Figure 12-27. A similar unit is known as a nozzle welder. It is portable and operates on larger-diameter pieces. It is used to weld nozzles into the wall of pressure vessels. Usually, a groove weld is made and special methods are used to follow the weld joint.

Other types of standardized welding machines are designed for maintenance work. This includes special types used for building up track shoes of crawler tractors, while other types are used for building up track idler rollers. This is routine, scheduled maintenance work performed in mines and quarries. Wear parts are regularly rewelded to build them up to size. The machines for built-up track shoes usually include several welding heads on a side beam carriage with limit switches that stop and start the arcs as the carriage progresses from one end to the other.

Another popular standardized welding machine is known as a strip splicer. These machines quickly splice strip or skelp prior to going into a roll-forming machine or tube mill. For thinner or nonferrous metals the gas tungsten arc welding process is used. They usually operate in conjunction with a loop in the production line. The ends of the strip are sheared, brought together, clamped, and welded so quickly that the tube or forming mill is not stopped.

Orbital welding machines for welding pipe and tubing can be considered as a standardized automatic welding machine. These machines are described in Chapter 25. The standardized automatic welding machines greatly increase the productivity of welding and should be used whenever possible.

FIGURE 12-27 Rotary spud welder.



12-5 DEDICATED AUTOMATIC ARC WELDING EQUIPMENT

A dedicated automatic arc welding machine is customized equipment designed to weld one specific part or a family of very similar parts on a high-volume production basis. Dedicated or customized machines are used whenever identical parts are manufactured in sufficient quantities or on a continuous basis. The automative industry and the appliance industry are major users of dedicated fixtures or automatic welding equipment. The very first automatic arc welding machine (Figure 12-28) was custom designed to automatically weld differential housings for automobiles.[3] This machine utilized continuous bare electrode wire and produced good-quality parts in the early 1920s.

A dedicated or customized arc welding machine is designed to weld one specific part and that part only. This type of equipment is sometimes called "hard automation." Some dedicated fixtures may allow for a family of parts that are very similar but vary in size or have only minor differences. They are quickly adjustable to allow for these differences. The customized dedicated welding machine incorporates arc motion, work motion, and work-handling equipment with appropriate controls and welding equipment.

The major disadvantage is the need to redesign or modify the dedicated machine when the design of the production part is changed. Another disadvantage is the need to keep the customized equipment operating on a full-time continuous basis. Dedicated welding machines are expensive.

Despite this, automatic welding with customized machines is being used more and more in the high-volume production industries. This is because it is the most economical welding production method, especially if it is continuously in use. It reduces labor requirements, produces consistent high-quality parts, maintains production schedules, and standardizes the cost of welded parts.

Customized or dedicated welding machines perform the entire welding operation automatically. The machine may be manually loaded with individual parts. Usually, it is manually unloaded but may be mechanically unloaded. The automated welding machine may be part of a total production line; it is integrated into the total production operation.

Dedicated or customized machinery can be classified according to the number of welding workstations and the number of arcs involved. A good example of a single arc–two station machine is shown in Figure 12-29. This is used for welding automobile torque converters. This machine is relatively simple because the weld joint is a circle; however, the torch is retractable to allow for loading and unloading. The impeller cover is a ¼-in. (6.4-mm)-thick steel stamping. The hub is a steel tube with

FIGURE 12-28 First automatic welding machine.

a 0.200-in. (5.1-mm) wall thickness. Two stations allow loading and unloading while the other station is welding. The parts are self-jigging because of the hole in the impeller and the collar on the hub. Part (a) shows the loading operation with the welding torch retracted. Part (b) shows the welding operation with the head in place, and part (c) shows the overall view of the machine during welding. Only one station welds at a time and a single power source is used. In normal use a curtain comes between the operator and the arc so that a welding helmet is not required. The centerline of the hub is at a 25° angle, which provides a fillet weld which has the proper contour for maximum strength. The gas metal arc welding process with argon–CO_2 shielding gas is used. Spatter is minimal and the quality of the weld is high. The completed torque converter housings are welded together at final assembly and are given a hydrostatic pressure test to assure good-quality welds.

The next example utilizes two workstations and two arcs at each workstation. In this operation a clutch or brake pedal for a recreational vehicle is welded. It is a three-piece assembly consisting of a hub, a steel arm, and a pedal. The welding sequence is shown in Figure 12-30. The two welding stations utilize the same welding operator and the same welding power sources. In both stations two arcs are operating simultaneously. On the left-hand station the hub is being welded to the arm by rotating the assembly approximately 180° and making two fillet welds simultaneously. The right-hand station uses linear travel with two arcs simultaneously to produce two fillet welds between the arm and the pedal. The operator works both stations, loading and unloading one while the other is welding. Cycle time is such that two arcs are continually welding. All four welds are made using gas metal arc welding with CO_2 shielding.

The next example is welding compressor housings used for refrigerators, air conditioners, and so on. This application is rather unique since the welding path is oval

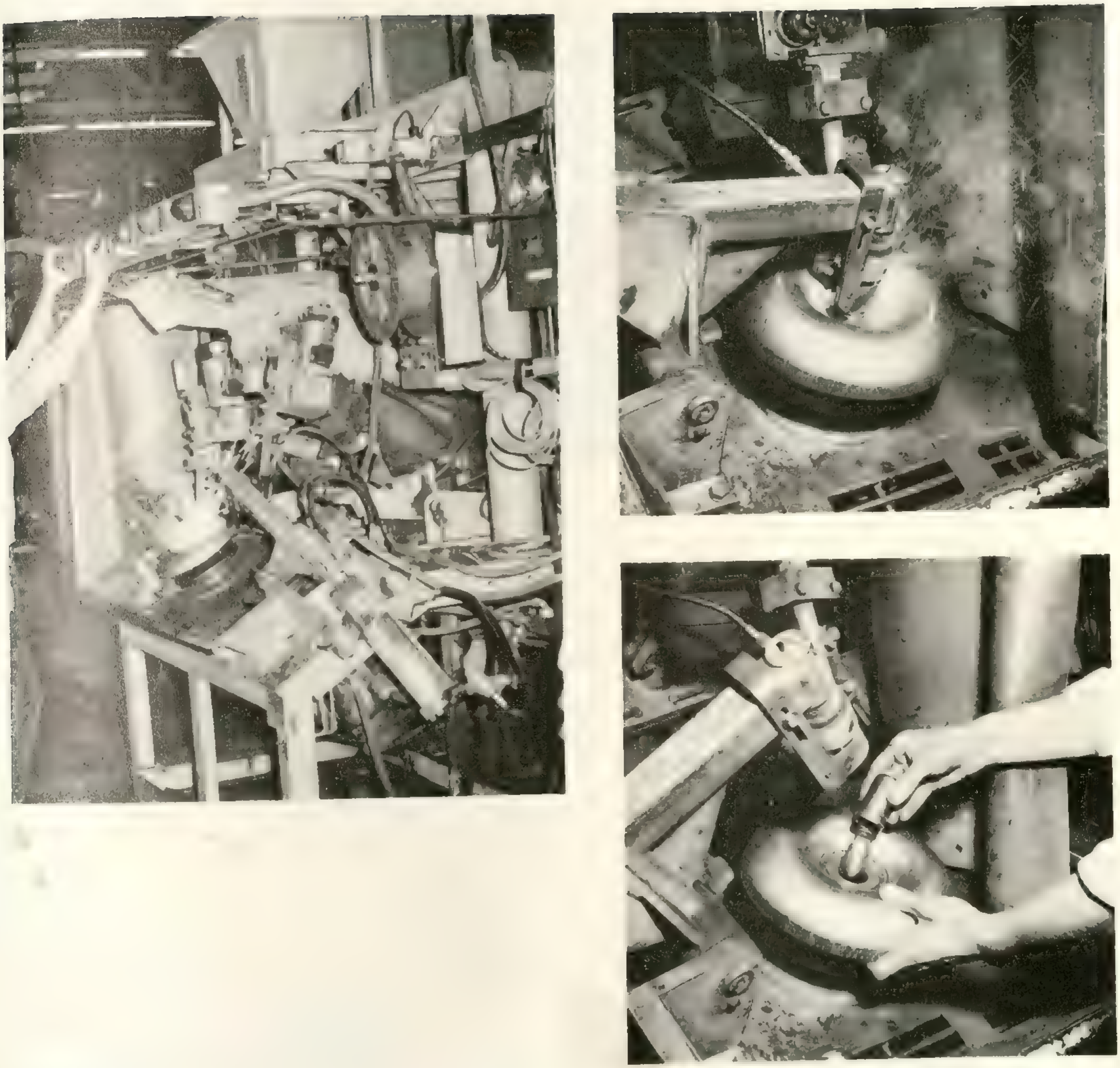


FIGURE 12-29 Welding torque converter.

and the dedicated machine is designed to allow for a family of similar housings to be produced with simple adjustments that can be made quickly. Figure 12-31 shows the customized machine for making a fillet lap weld joint around the periphery of the housing. The parts are thin-gauge steel. This involves a complex motion system in which both the welding head and the part move simultaneously. Gas metal arc welding is employed and the welds are of extremely high quality, due to the requirements of this product.

Automatic welding with dedicated machines is not restricted to the automotive and appliance industry. It is being used for producing large structural weldments. In this example a dedicated machine is simultaneously making six welds to join three preformed stiffeners to the deck of the approach to a large bridge. These assemblies were fabricated of steel plates 1 in. (25 mm) thick by 10 × 50 ft (3 × 15 m) with three preformed stiffeners ½-in. (12.5 mm) thick welded to them. These panels were then assembled and welded into a 40 × 50 ft (12 × 15 m) assembly and moved to the erection site. Six arcs are used simultaneously to weld the stiffener sections to the 1-in. steel deck plates. A gantry-type welding machine carries all the welding heads, controls, and electrode wire sup-

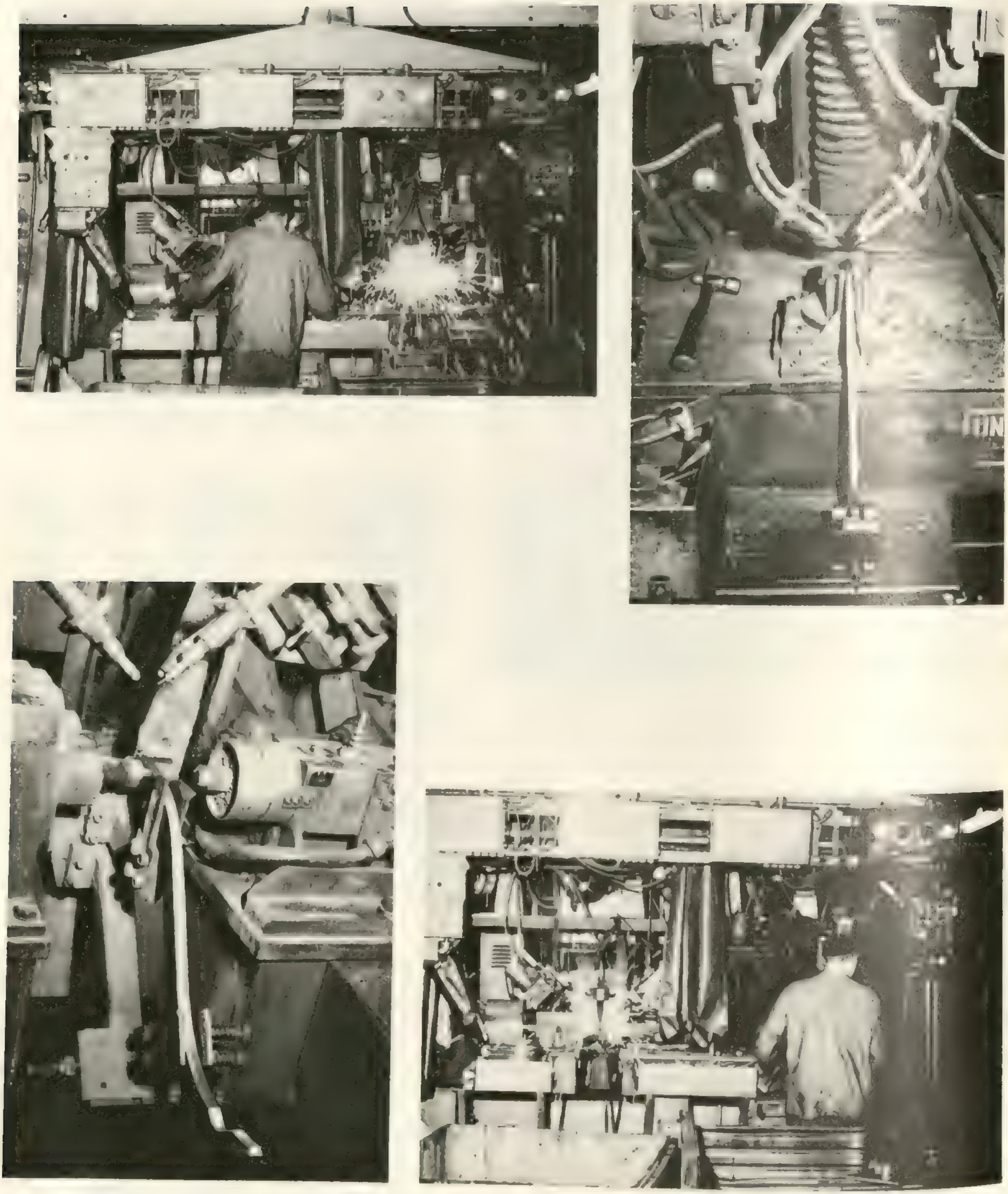
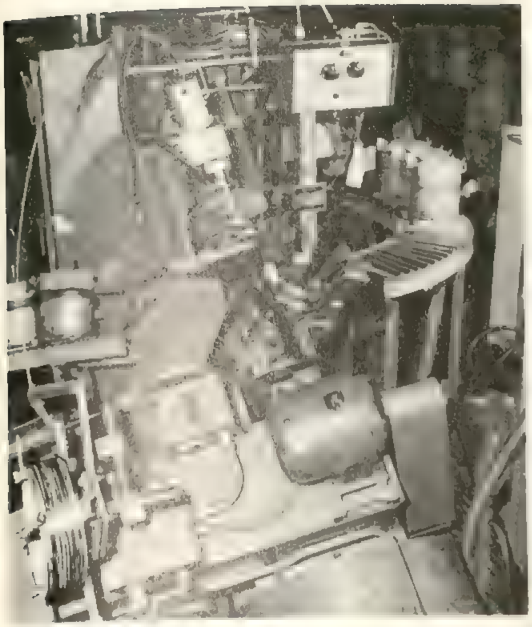


FIGURE 12-30 Welding brake and clutch pedal.



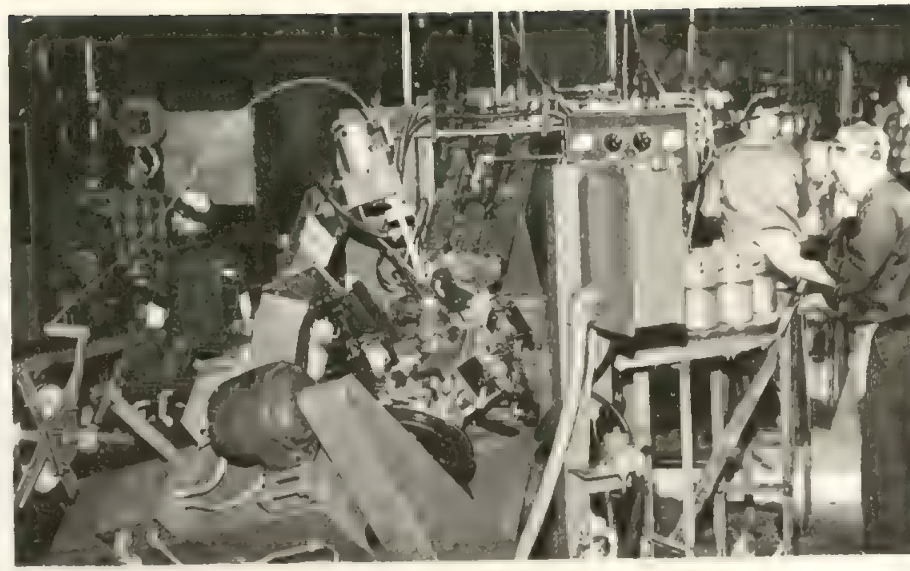


FIGURE 12-31 Welding compressor housing.

ply (Figure 12-32). The figure shows the welding with the six heads being used simultaneously. Flux-cored arc welding utilizing CO_2 gas shielding is employed. High-quality full-penetration welds were required which passed the necessary structural qualification tests.

Dedicated automatic welding machines are not all restricted to continuous electrode wire processes. The final example is a machine for producing electric motor parts. It is used for welding the stamped laminations together (Figure 12-33). These assemblies are made on equipment which includes two welding stations and two welding processes. The first machine, which has four positions, clamps and holds the lamination assembly in the proper position and moves it vertically in front of two

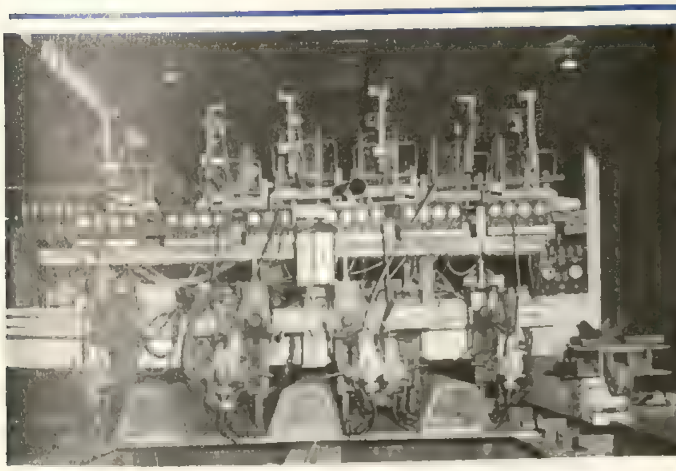


FIGURE 12-32 Welding stiffeners to bridge neck.

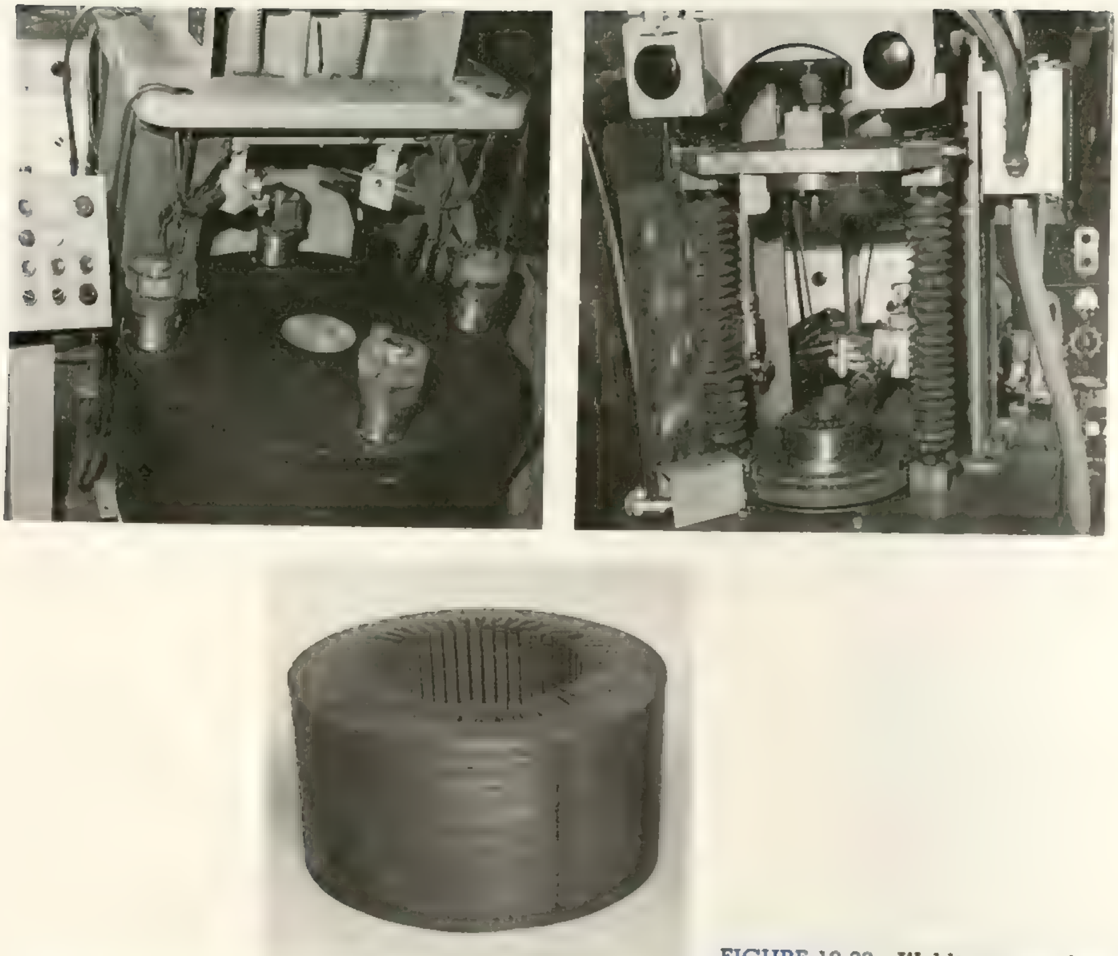


FIGURE 12-33 Welding motor laminations

gas tungsten arc welding torches. The workstation rotates and makes two more welds. The final operation, done on a second machine, welds a cap ring to the stator. A gas metal arc plug weld is made through prepunched holes. The mandrel, which holds the stator, turns after each plug weld is made to bring the next hole in line with the torch. The total operation, which combines two welding processes and two stations, will produce hundreds of units per hour.

Many companies produce dedicated or hard automation welding equipment. These are relatively expensive since they are designed for a particular application. However, the payback period is short provided that there is sufficient production volume. The disadvantage is that the machine must be rebuilt whenever the design of the product is changed.

12-6 FLEXIBLE AUTOMATION OF WELDING

Today there are greater demands on the manufacturing industry than ever before. Customers want shorter delivery time and require a greater variety of products. At the same time, the product's lifetime is shorter and manufacturing batch or lot sizes are smaller. A response to these demands has been the development of **flexible manufacturing systems** (FMS). Flexible manufacturing systems are being used to replace small batch and continuous manufacturing operations without losing the economies of volume production. The flexible manufacturing system was developed during the 1960s by the machine tool industry with government and customer assistance.

A study by the U.S. Congress, Office of Technology Assessment,[4] indicated that discrete manufacturing could be divided into three categories, based on the volume and variety of products (Figure 12-34):

1. Single-piece parts or an extremely low volume of similar items
2. Batch production of medium lot sizes
3. Continuous production or a high volume of similar parts

Job shop production is low-volume production with a lot size as small as one piece, that is, custom produc-

Type of Production	Job Shop	Batch	Mass
Lot size (volume)	Low volume	Medium volume	High volume
Large complex parts	1–10	10–300	Over 300
Small simple parts	1–300	300–15,000	Over 15,000
Weld setup	Manual setup	Fixture—manual loading	Fixture—automatic loading
Welded production	Manual or semiauto weld	Standardized welding machine	Dedicated welding machine
Estimated percentage of U.S. production	10–20%	60–80%	20–30%

FIGURE 12-34 Characteristics of metal working production by lot size.

tion of 1 to 10 parts if it is a large complex part, or a volume of 1 to 300 units if it is a small simple part. *Batch production* is a moderate to medium lot size of 10 to 300 large, complex parts, or 300 to 15,000 small, simple parts. *Mass production* is high-volume production, usually over 300 large, complex parts, or over 15,000 small, simple parts. This usually means continuous operation of dedicated production equipment. These may be arbitrary figures, but are based on this study.

Job shop production involving single units or small lot sizes is very labor intensive. The parts produced are very expensive. There is insufficient volume to justify special machines or dedicated equipment.

Batch production involves medium-volume lot sizes. This type of production can justify simple fixturing and standardized machines to make weldments with less labor. This category is still relatively labor intensive but produces parts at a lower cost.

Mass production involves high-volume or perhaps continuous production. This type of production justifies welding customized equipment. The amount of labor per part is minimum, labor efficiency is maximum, and the end product is the least expensive.

The flexible automation of welding that makes use of flexible manufacturing systems can make batch manufacturing as efficient and productive as mass production. Carried to its ultimate, it could even make job shop production much more efficient and productive and greatly reduce the cost of "one-only" production.

Robotic arc welding is the obvious answer for flexible automation of welding. The use of a robot and a simple welding fixture that can be mounted on a work motion device is the key to reducing welding costs. A computer program is developed for each part. The program is placed in memory and used every time the particular part is manufactured. The setup time is minimal and the robot is kept busy welding many small lot sizes of parts all day long. It allows the capability of changing from one part to another quickly, and needs only a positive locating point to align the robot's welding torch with the parts being welded. Extremely small or medium-size lots can be processed economically in this manner. A different simple locating fixture is used for each part and for welding the lot size required.

Robots are expensive and must be kept busy on a full-time basis to be acceptable economically. There is another way of accomplishing the economy of mass production of small parts produced in small lot sizes. Typical parts are shown in Figure 12-35. This can be done

FIGURE 12-35 Typical parts manufactured with flexible welding equipment.

with a flexible welding system that is computer controlled. A flexible automatic welding station for welding small simple parts is shown in Figure 12-36. This workstation costs less than half that of a robot cell. The welding sequence for each workpiece is programmed and stored in the computer memory. A simple holding and locating fixture is provided for each weldment. When the part is to be produced, the operator places the fixture on the table and calls up the program from memory. This takes very little time. For production welding the operator loads the fixture, presses the start button, the machine makes the weld, and the operator unloads the finished weldment. This machine can be programmed for linear arc motion

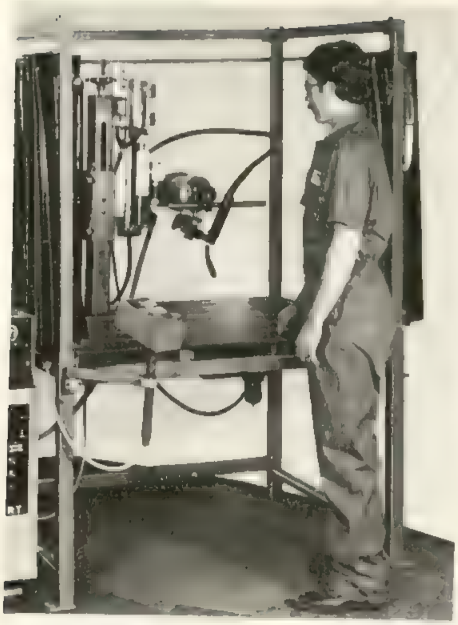


FIGURE 12-36 Flexible welding workstation with computer control.

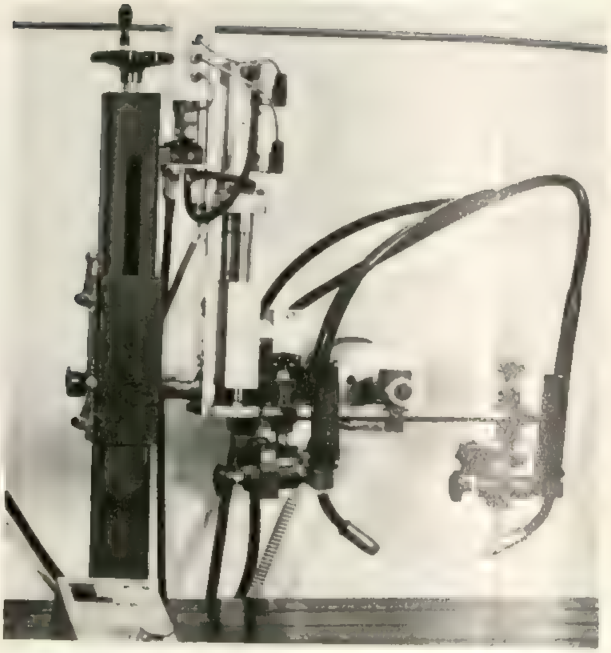
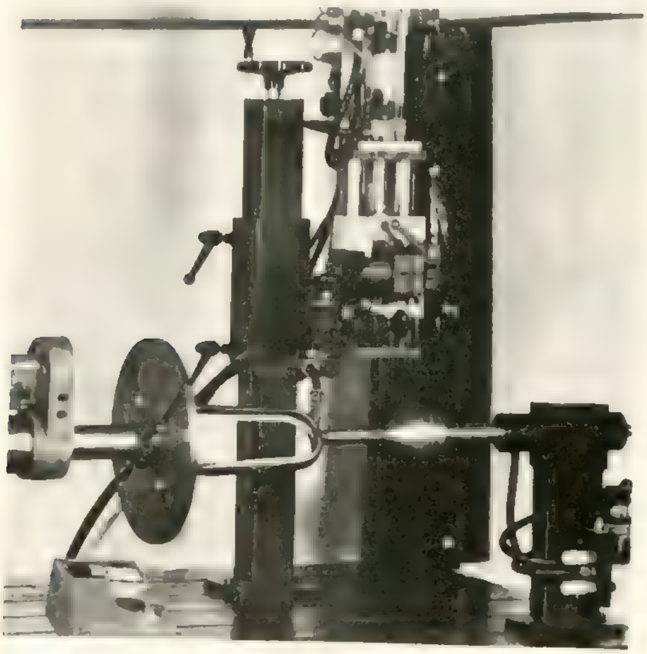


FIGURE 12-38 Two-torch welding system.

using one or two torches. It can be arranged for rotating work or arc motion with the axis of rotation vertical or for head and tail stock rotary motion with the axis horizontal. Figure 12-37 shows the head–tail stock system with a bicycle part being welded with rotation about the horizontal axis. Figure 12-38 shows the two torch welding system with linear motion. The equipment is quickly changed over from one type of motion to another. It is easily adapted to product mix changes and to small batch sizes. This is flexible automation of welding. It is used for more and more short-run applications on simple parts. It will eliminate complex dedicated fixtures and will find increasing acceptance in volume production plants. This equipment is much less expensive than a robot, yet will make the welds in the same time.

FIGURE 12-37 Head stock/tail stock system welding bicycle part.



12-7 ARC WELDING ROBOTS

Arc welding robots have become popular in the last few years; however, robots have been around for many years. Joseph Engleburger, the father of modern robots, developed a machine in the mid-1950s and gave it the name *robot*. This was based on the Czech word robota, which connotes forced labor that was depicted as a kind of automation in Karel Capek's 1920 play entitled *R.U.R.*[5] Today the accepted definition of the Robot Industry's Association defines a robot as a "reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices, to variable programmed motions for the performance of a variety of tasks." The Japanese define the robot as a three-axis programmable tool. This difference in definition explains why there are many more robots in Japan than the United States.

Robots were introduced to North American industry in the early 1960s; however, it was not until the mid-1970s that robotic arc welding was used in production. Robotic welding grew rapidly in the early 1980s because of the emphasis by the automotive industry. In the

mid-1980s other manufacturing companies started using welding robots, and today their use is widespread and growing.

The automotive industry first used robots for spot welding (Figure 12-39). The robot replaced a person using spot welding guns. This has completely changed the automobile body production line. Today almost every automobile body produced is spot welded with a robot.

All arc welding robot systems consist of a number of major components (Figure 12-40). The part referred to as the robot is known as the manipulator or "mechanical unit," which performs the manipulative functions. The brain of the robot is the controller, and there are many auxiliary devices to make the robot more productive.

The robot manipulator is a series of mechanical linkages and joints capable of moving in various directions in order to provide motion. The mechanisms are driven by linear actuators, which may be hydraulic or pneumatic, and or rotary motors, which may be hydraulic or electric. They are coupled together by mechanical links and may be direct driven or driven indirectly through gears, chains, or screws. There are different designs of manipulators, ranging from three-axis to multiple axes.

FIGURE 12-39 **Robots handling spot welding guns on auto-body line.**

The mechanical manipulator can be categorized by its general design. The more common types of manipulators are the (1) cartesian coordinate, (2) the cylindrical coordinate, (3) the spherical coordinate, (4) the anthropomorphic coordinate, (5) the gantry, and (6) the SCARA type. Each type has specific advantages and features, but all can be used to move a welding torch to make welds.

The complexity of the robot is usually described by the number of axes or "freedom of motion" that it is capable of providing. To provide more motion, most robots have a two- or three-axis-of-wrist motion in addition to its basic motions. In selecting robots it is important to understand the work envelope in which the robot can make welds. Each type of robot manipulator has a different work envelope configuration. The shape and size of the work envelope relates to the motions and size of linkages of the robot. Arc welding robots were originally designed to match the working area of a human being.

Robot Manipulator Configuration

Four of the six types of robots are shown in Figure 12-41. The first is the cartesian coordinate robot, based on the three-plane drawing system used for blueprints. It is often called the rectangular coordinate system since it moves within a box-shaped volume based on the *x*, *y*, and *z* directions. The direction *X* stands for longitudinal motion in a horizontal plane. *Y* stands for transverse or "in or out" motion in a horizontal plane, and *Z* stands for up-and-down motion in a vertical plane. It has sliding motion in all three directions. It has three motion axes: longitudinal, transverse, and vertical. Its work envelope is a rectangle box.

The second is the cylindrical coordinate robot. This robot type is similar since it uses sliding motion for two directions, the vertical and one extension, but has one rotational or swing motion. The work envelope is cylindrical in the plan view and rectangular in the elevation. The arm holding the welding torch moves up and down the mast and swings about the mast with less than a full circle. The torch extends and retracts.

The third is the spherical coordinate robot, also known as a polar coordinate robot. This robot type has one sliding motion and two rotational motions. One is around the vertical post, and the other is around a

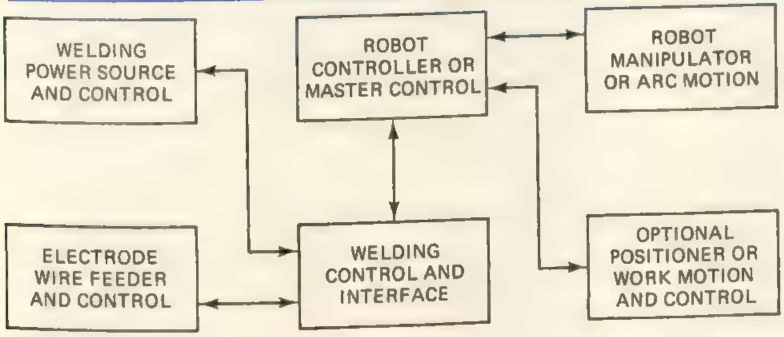


FIGURE 12-40 **Robot arc welding system.**

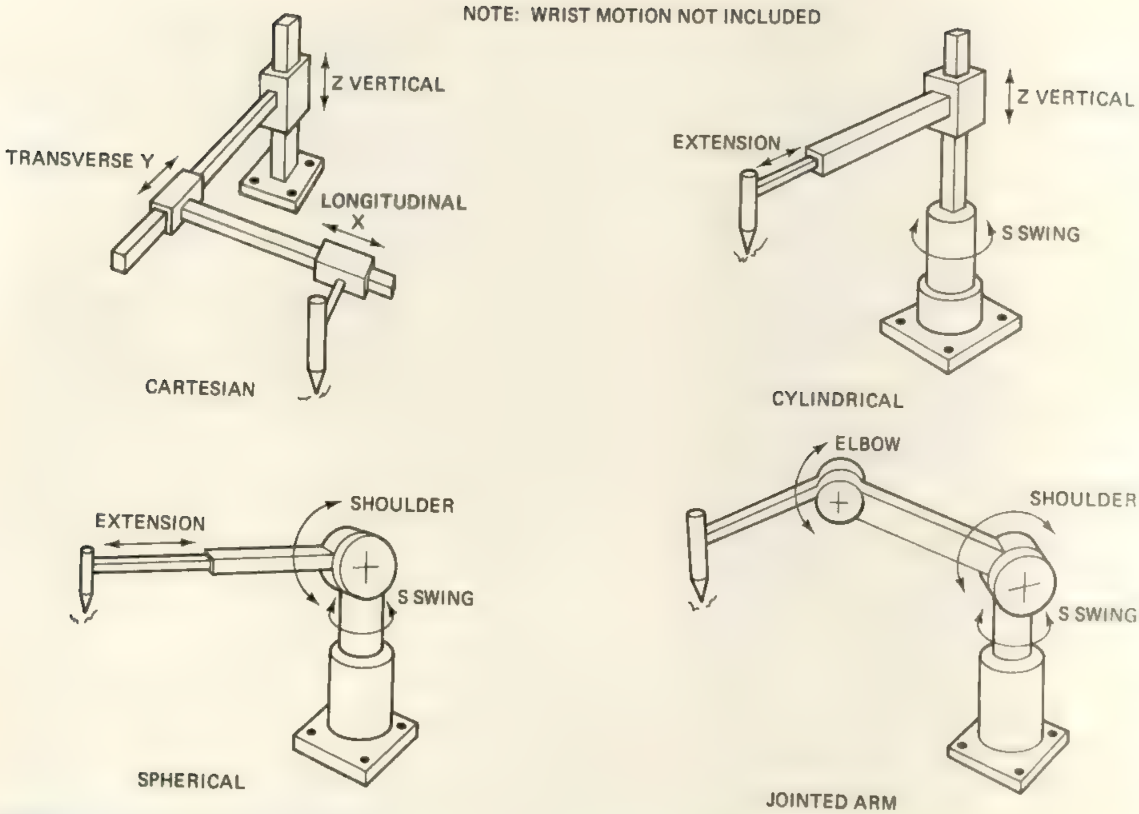


FIGURE 12-41 Four types of robots.

shoulder joint. The mechanism holding the arm swings about a vertical axis and rocks up and down about a horizontal axis. The arm slides to extend and retract. The work envelope is spherical with a similar plan view as the cylindrical coordinate motion robot, but with an elevation view showing the rotational motions based on the shoulder rotation.

The fourth robot is the anthropomorphic robot, or revolute or jointed arm robot. The motions are all rotational with no sliding motion. The work envelope is irregularly shaped in the vertical plane and about two-thirds of a circle in the horizontal plane. This type of robot swings about its base to sweep the arm in a circle. It bends the upper arm forward and backward at the shoulder and raises and lowers the lower arm at the elbow.

The fifth robot, which can be considered as having a cartesian coordinate motion, is the gantry robot (Figure 12-42). The gantry is only part of the total motion since a jointed arm robot or a two- or three-axis wrist is attached to the gantry carriage to provide maximum movement within the work envelope. Its work envelope is a large rectangular box.

The sixth robot is the SCARA. SCARA is an acronym for "selection compliance assembly robot arm," also known as a horizontal articulate robot. Some SCARA robots have all rotating axes and some have one sliding axis in combination with a rotating axis. SCARA robots have four axes of motion but do not have much vertical travel. They are used for welding primarily in a single plane. Their work envelope is a flat rectangular box.

There can be combinations of these types of motion systems for special applications. The work envelopes of different makes of robots of the same type are similar. The variations are due to different lengths of arms and links. The jointed arm or anthropomorphic robot is the most popular. The basic movements are shown in Figure 12-43. The work envelope of a typical jointed arm robot is shown in Figure 12-44.

The method for attaching a welding torch or gun is by means of an adapter attached to the wrist. Two different methods of attachment are shown in Figure 12-45. The adapter may have a breakaway feature, which avoids damage if the torch crashes into the work or fixtures. The wrist, which is attached to the work end of the robot upper arm, allows two or three additional axes of motion. They are very similar to the human wrist. These motions are known as pitch, roll, and yaw, which are boating terms, or bend, twist, and tilt. Figure 12-46 shows the wrist motions with a welding torch attached. Two- or three-axis wrists are used with arc welding robots.

The body motions and wrist motions allow the welding torch to be manipulated in space in almost the same fashion as a human being would manipulate it. This allows the torch angle and travel angle to change in order to make good-quality welds in all positions. They are also

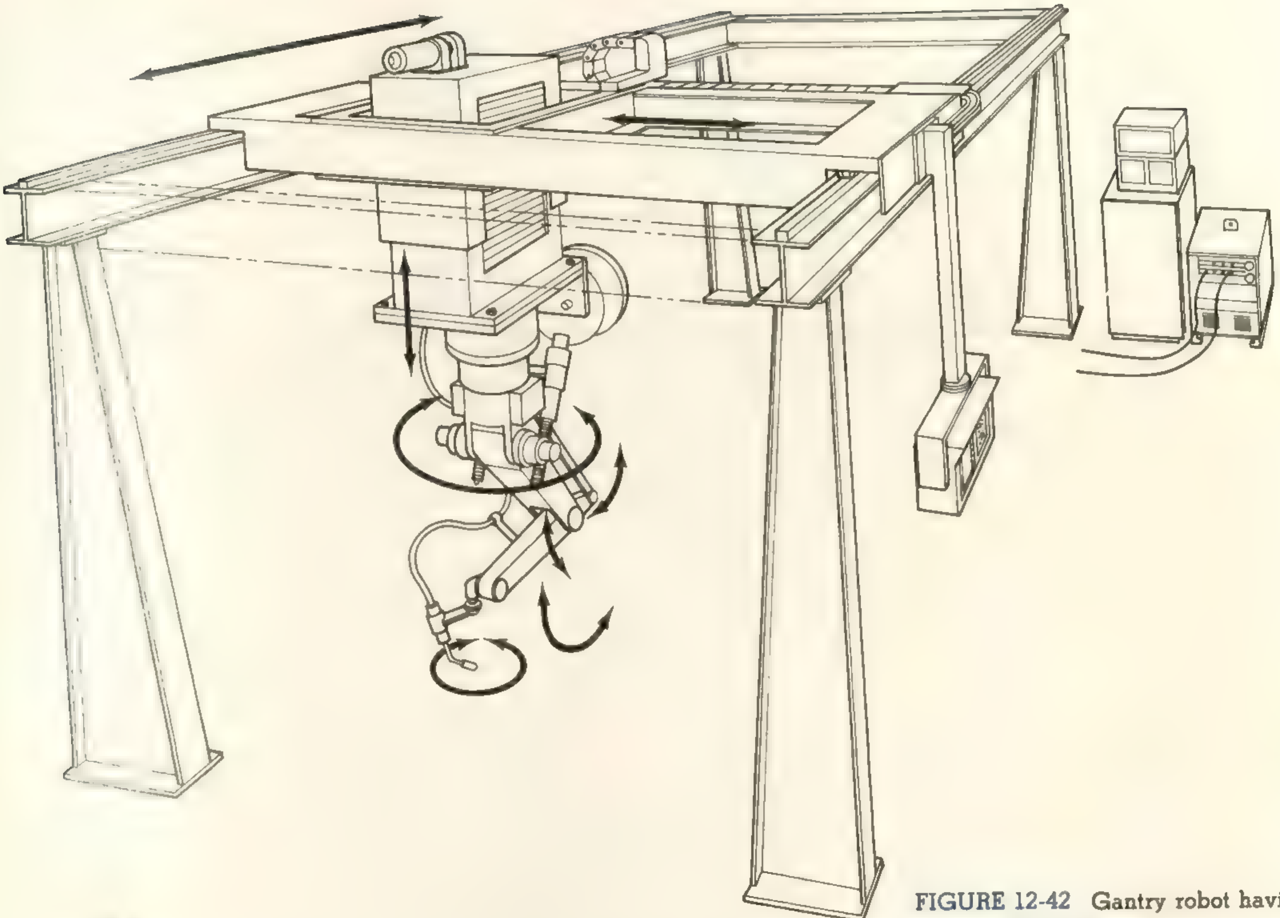
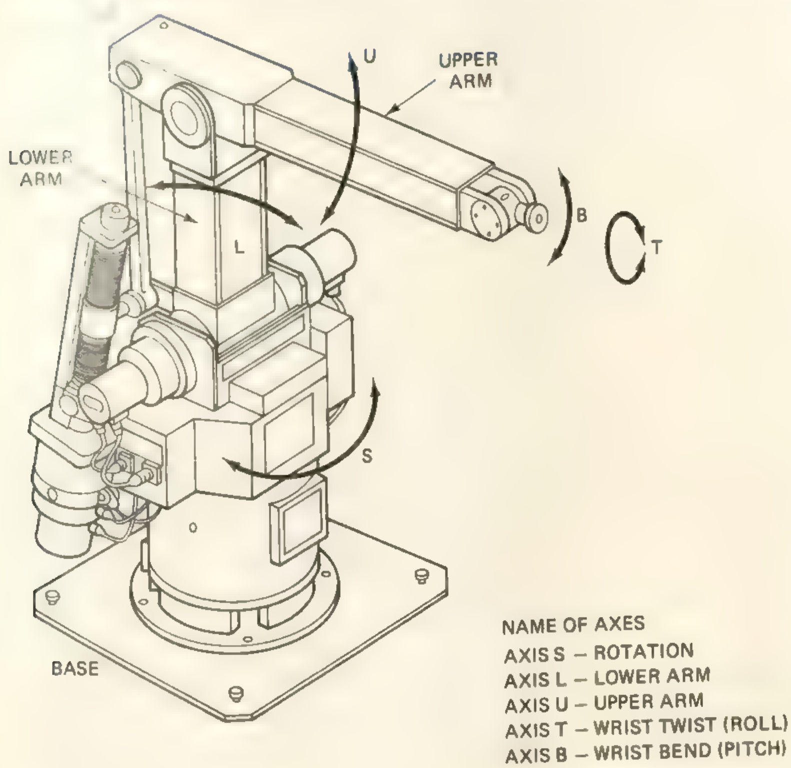


FIGURE 12-42 Gantry robot having eight axes of motion.

FIGURE 12-43 Basic movements of a jointed-arm robot manipulator.



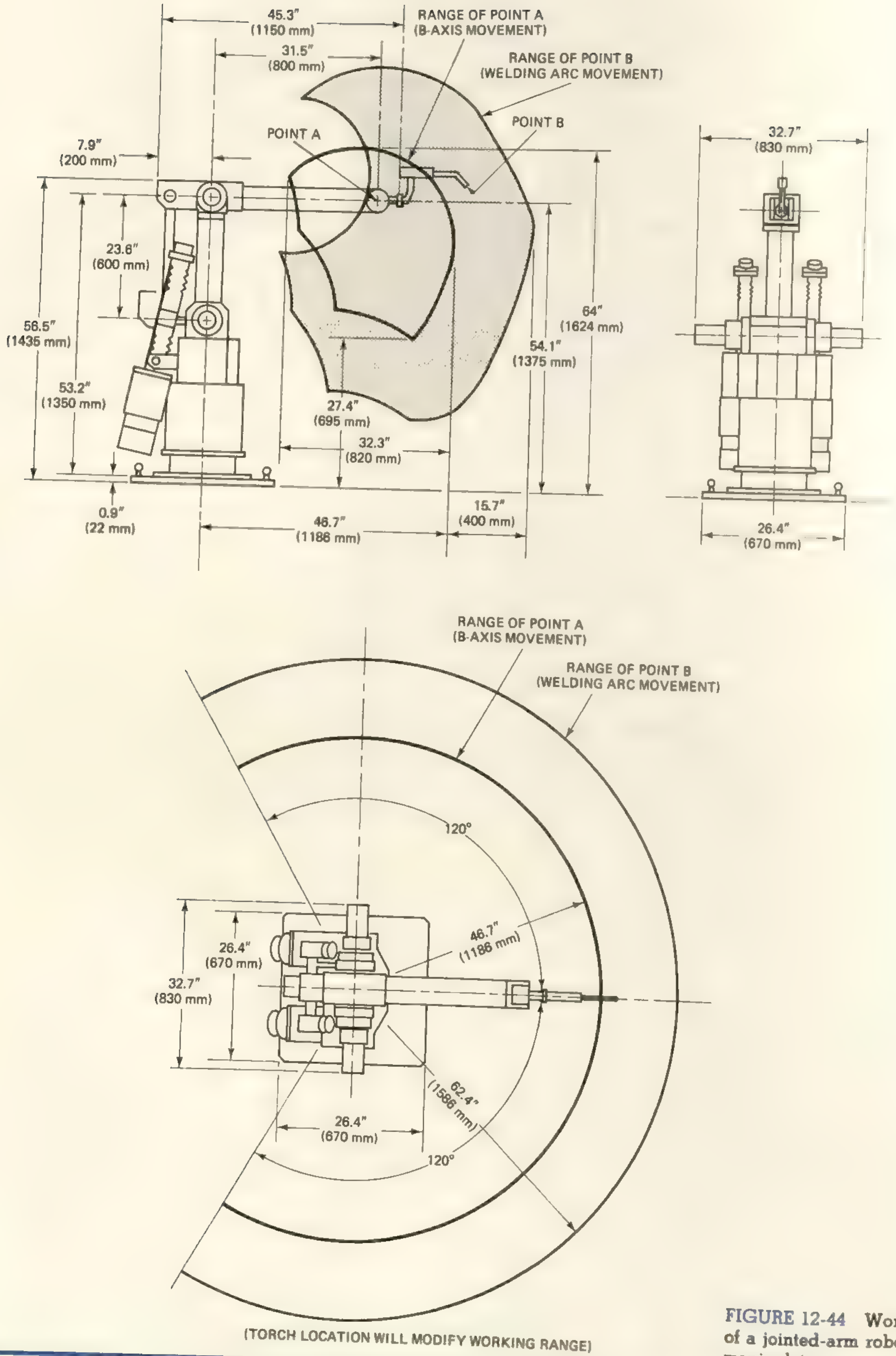


FIGURE 12-44 Work envelope of a jointed-arm robot manipulator.

FIGURE 12-45 Methods of welding gun attachment.

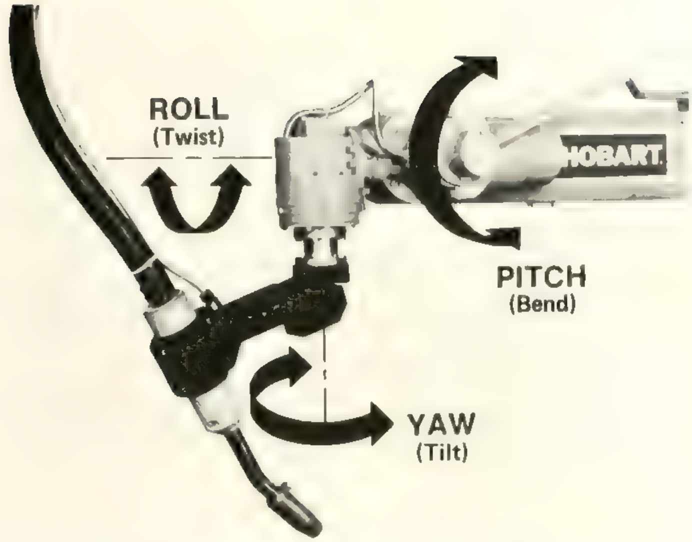


FIGURE 12-46 Wrist motions.

required in order to reach difficult to reach areas. Even so, a robot cannot provide the same manipulative motions as a human being, but it can come extremely close.

Additional axes are added when the robot is mounted on a moving carriage. This will add an additional axis of motion. A work-holding device can add an additional axis of motion. This is usually rotation and/or tilt, which will add two more axes of motion. A jointed arm robot with a three-axis wrist working with a two-axis manipulator would have eight axes of motion.

In selecting a robot it is necessary to determine its work envelope and reach and the number of axes of torch motion. This will allow you to determine if the robot will weld the weldment in question. This is difficult to determine without making tests; however, computer design programs are available that will help decide whether the robot can accommodate the weldment. An actual test is the positive method.

In selecting a robot it is important to determine the travel velocity while welding and while not welding, known as "air cut time." The welding speed must be compatible with the welding process and procedures to be used. The air cut time movement when not welding should be a minimum; the travel velocity when not welding should be high.

An important factor is the repeatability of the robot. This is the closeness of agreement of repeated position movements under the same conditions to the same location. This means to move the welding torch to the same point every time it goes through its program. Most electric robots provide a maximum variation of ± 0.015 in. in robot movement for repeated returns to a programmed point. This is affected by operating speed and is acceptable for gas metal arc welding. For gas tungsten arc or plasma arc welding a tighter tolerance is required

and a repeatability of ±0.008 in. is desired. This information is provided by manufacturers' specifications; however, a test provides positive data.

Accuracy of robot movement is also very important. This is the degree to which the actual position corresponds to the desired command position. This is measured by comparing the command position to the actual position.

Resolution is also very important. This is a measure of the smallest possible increment of change in variable output of the robot. It is determined by the ability of the position feedback encoders or resolvers to determine the location of a particular joint and the position of the endpoint, called the "tool center point."

Another factor is the weight-carrying capacity of the robot. This is the weight that it will accommodate in its normal operating envelope at normal travel velocities on the end of the wrist. Weight carrying capacity should accommodate the welding torch, the torch breakaway devices, water and gas hoses, current-carrying cable, and in some cases the electrode wire feeder or feedhead and the electrode wire.

The type of motion drive system is extremely important, as well as the type of position feedback sensors. The motion should be smooth at all times in all positions. Electric drive robots are most widely used for arc welding. Hydraulic drives can be used for painting or spot welding since accuracy or repeatability is less critical. The electrical robots are more repeatable since hydraulic systems tend to drift during warm-up and during operation. In addition, hydraulic robots may have oil leaks which could be a fire hazard or could leak on the work and create a defective weld. Finally, consideration should be given to mounting position, base height adjustment, manipulator weight, environmental limits, and approvals.

A typical robot installation is shown in Figure 12-47. This shows the robot manipulator and robot controller, the workpiece positioner and controller, the welding power supply wire control and interface, and the electrode feeder and control. The robot controller is described in Section 12-8.

Robot Welding Applications

Robots are welding many, many different kinds of parts. They can weld just about anything that a human being can weld. A few examples are presented to show the diversity of types of weldments made by robots.

Case Study: Tubular Welded Product This automotive manufacturer had been semiautomatically welding car seat frames in dedicated fixtures. The need was to handle more different varieties of frames and to increase production. They did the following: Fixtures were modified to handle more than one size of frame. Robots and positioners were installed. The fixtures were mounted on positioners and two positioners were used with each robot. Five parts are required to build the frame. The major part is thin-wall small-diameter tubing. The other parts are sheet metal stampings. Tack welding is not used. The operator loads the fixture and the frame is completely welded before removing from the fixture. One operator tends two robots loading and unloading workpieces on one positioner while the robot welds on the other. Six robots are producing over 60,000 frames per month. Improved quality, reduced production costs, virtually eliminated scrap, and minimized inspection time resulted from changing from semiautomatic to robotic welding of this application, shown in Figure 12-48.

Case Study: Sheet Metal Assembly This manufacturer of health care equipment wanted to remove welders from routine work and from the welding environment.[6] They also wanted to reduce costs and wanted to improve quali-

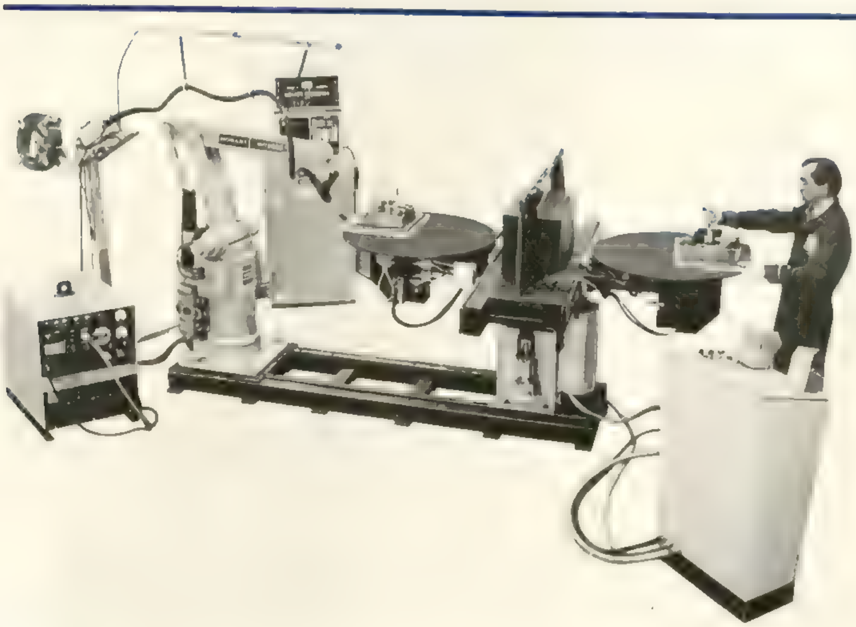


FIGURE 12-47 Typical installation of jointed-arm welding Robot.

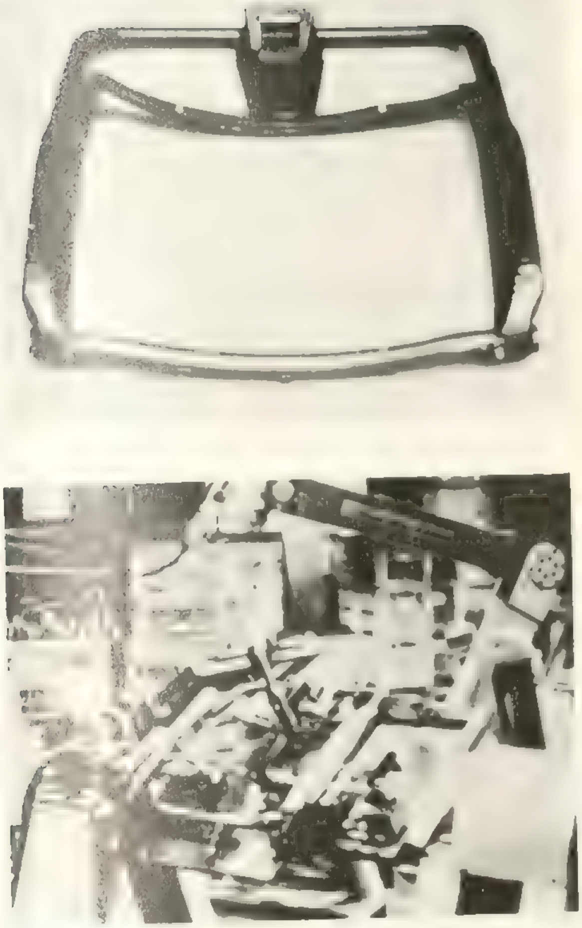


FIGURE 12-48 Tubular product.

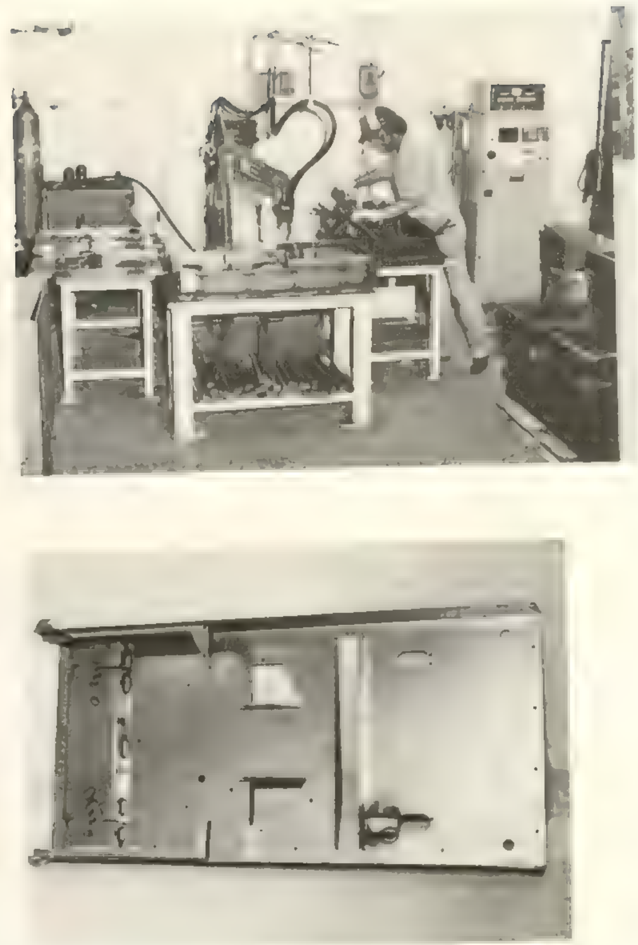


FIGURE 12-49 Sheet metal assembly.

ty in their product. The primary weldment is a fairly large sheet metal part (Figure 12-49). The work cell consisted of one robot and three workstations, all within the robot work envelope. The fixtures used previously with manual welding were upgraded for robotic welding. One operator mans all three workstations; however, an operator start-and-stop control panel is located in each station. Each fixture is on a fixed table. The operation operates three shifts a day and has reduced production costs by using less electrode wire and less CO_2 shielding gas in addition to increased welding speed. The quality of welds is very good and consistent, so that fillet weld sizes can be reduced. The productivity has increased over 200% since adopting the robot welding operation.

Case Study: Pipe Welded Assembly A diversified manufacturer of heavy equipment was seeking a way to reduce costs with small lot sizes and short production runs.[7] A portion of their work involved pipe fittings that required high-quality welds. Short runs are from 25 to 200 parts, and there are approximately 35 different welded assemblies. The company selected a two-station, five-axis work positioner and elected to have different fixtures on each end of the turnaround positioner. An assembly that is similar but of different sizes is shown in Figure 12-50. This is a flange-to-tee welded assembly. Switching to robotic welding has increased productivity since the operator sets up workpieces of various size and types on one end of the turntable while the robot is welding at the other end. This robot utilizes the through-the-arc welding seam tracker, which provides good-quality welds for every weld, even though fitup may not be perfect. The pipe assemblies are welded to strict code requirements.

Case Study: Gas Tungsten Arc Welds Not all robot welding is done by the gas metal arc process. Gas tungsten arc is being used for more and more applications. This aerospace supplier produces accessories for jet engines.[8] The material is thin and medium-thick stainless steel and nickel alloys. This company selected the dual-station positioner and an inverter-type 150-A power source. The material thickness ranged from 0.032 to 0.215 in., which required a wide range of welding currents. The robot was equipped with an automatic arc length control (AVC) operating through the robot software. Precision and repeatability has been excellent and the resulting weldments are more consistent than those produced previous-

FIGURE 12-50 Pipe welded assembly.

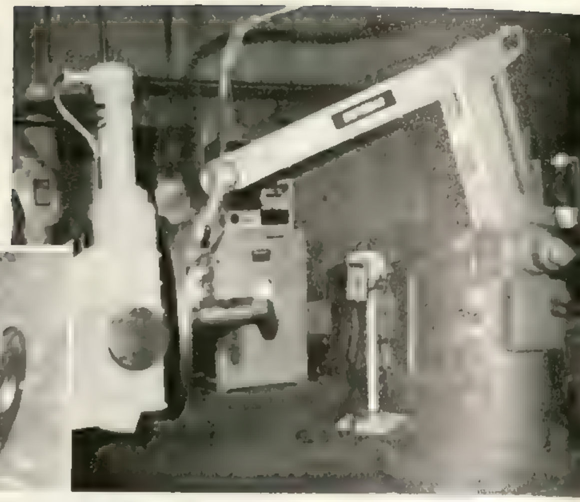
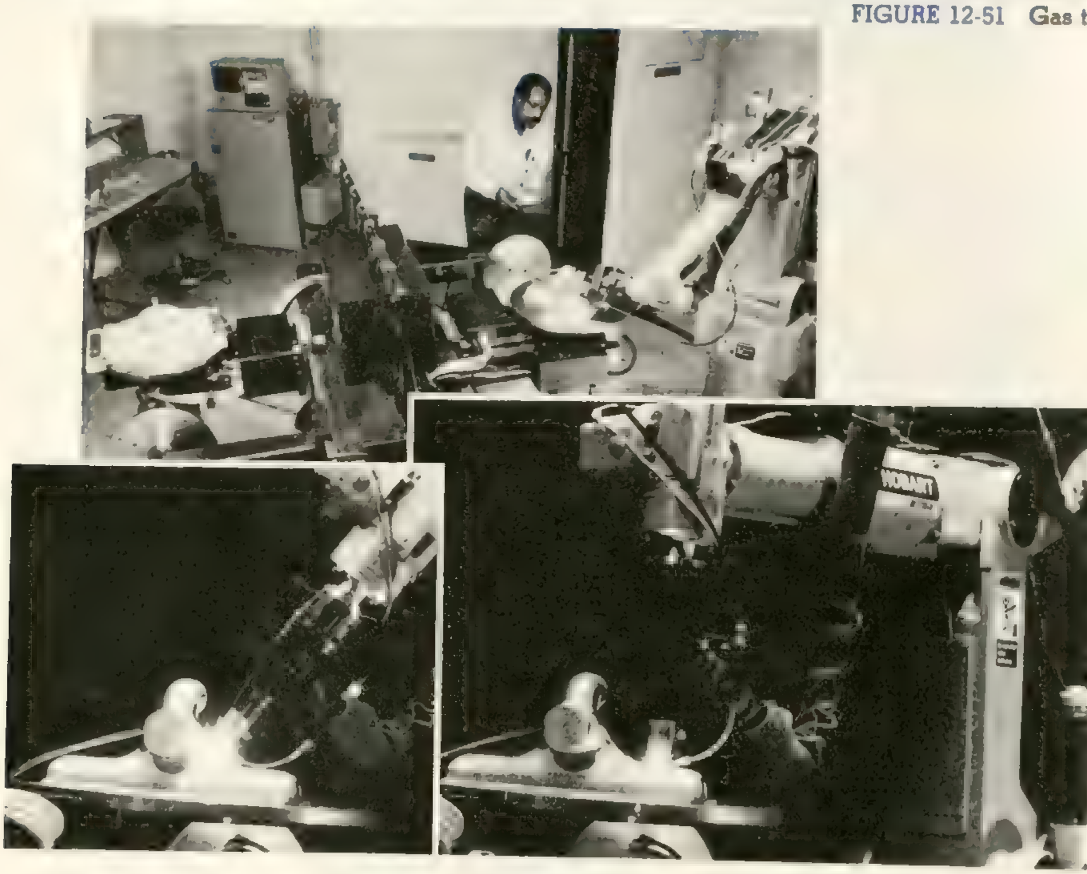


FIGURE 12-51 Gas tungsten arc welding.



ly. Cold wire feed is used for heavier materials but not for the thin materials. This application is shown in Figure 12-51.

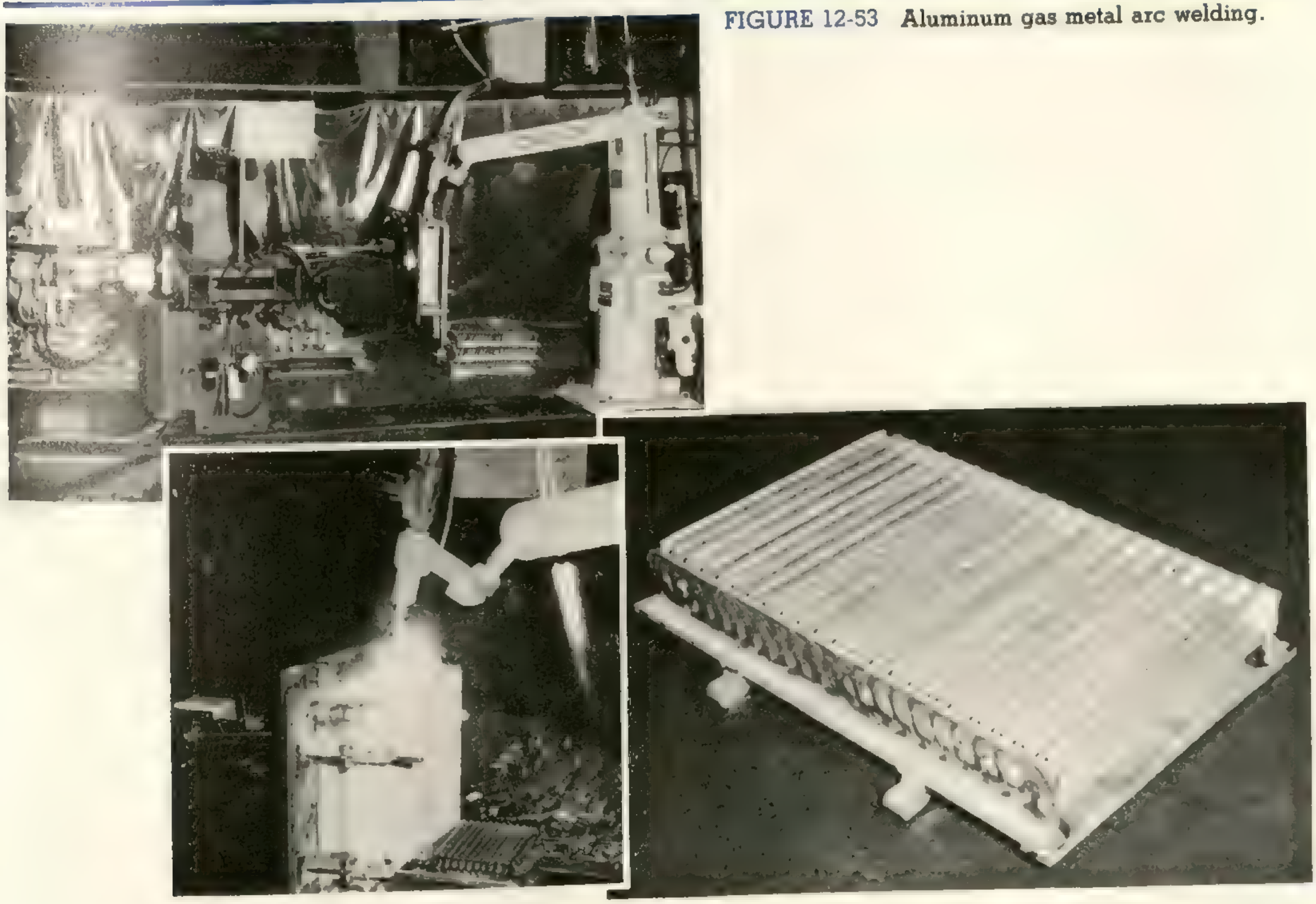
Case Study: Automotive Front Cross Member The automotive industry uses arc welding robots because of the large volume of parts produced on a continuous basis. However, automotive companies have yearly model changeovers. Changeover expense can be minimized by using robots and dedicated holding fixtures rather than dedicated arc welding machines. The product is an automobile front cross member made from two heavy sheet metal stampings and miscellaneous smaller stampings. This assembly, shown in Figure 12-52, requires 56 in. of intricate curved welds. It is first spot welded together and then arc welded. The operation is completely automated, including transporting the workpiece from station to station. The conveyor transports the workpiece under the positioner, which clamps it and rotates it 180° for welding position. Following the weld cycle, the finished workpiece is automatically released onto the conveyor and transported to the next workstation. This operation is in

continuous use 8 hours a shift, two shifts a day, 6 days a week. Quality is improved and costs are reduced with robot welding.

Case Study: Aluminum Gas Metal Arc Welding Aluminum is welded with the gas metal arc process using robots. A supplier to the defense industry is producing aluminum louvered grill assemblies.[9] The company required increased production and selected a five-axis robot with a five-axis double-ended dual-station work positioner. The parts were semi-self-jigging but required holding fixtures to keep parts in proper alignment. The holding fixtures were attached to the turntables on each end of the positioner. The system utilizes a push-pull wire feeding system with a water-cooled torch. Approximately 150 in. of weld is required to produce each louver. With the robot, weld quality and consistency has greatly improved and warpage has been greatly reduced. Productivity increased and exceeded production requirements. Welding these louvers is shown in Figure 12-53.

FIGURE 12-52 Auto front cross member.

FIGURE 12-53 Aluminum gas metal arc welding.



12-8 CONTROLS FOR AUTOMATIC ARC WELDING

When making a weld it is always the intent to produce a perfect weld. In any of the methods of application, except manual welding, some sort of a control or mechanism is required. This control is necessary to run a welding program. A welding program is always employed consciously or unconsciously whenever a weld is made. The program or welding procedure is the parameters for making the weld. In manual welding these are established and controlled by the welder. In semiautomatic welding a control mechanism in the wire feeder actuates electrode wire feed, and starts the welding current and shielding gas flow when the welder presses the gun trigger. This is done by a weld controller, which is a series of electrical circuits that causes these different activities to occur.

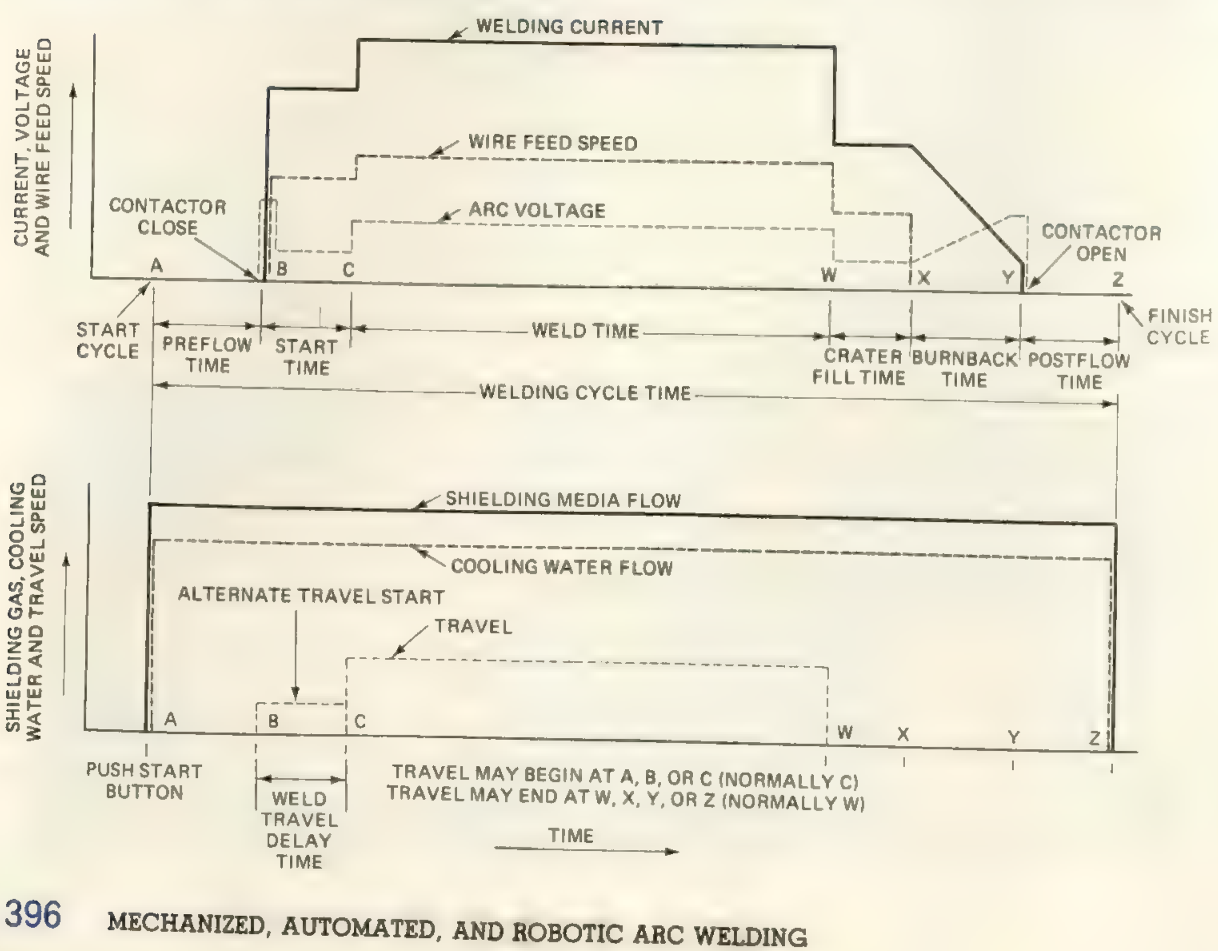
Mechanized and automatic welding have more complicated programs and require the control of additional functions, including travel or motion, and perhaps torch motion or fixture motion. All motion functions are sequential. Automated welding, which varies weld parameters in accordance with actual conditions, has a complicated computer control system which includes sensing devices and adaptive feedback.

Automatic Welding Controllers

Programmers are designed to execute a welding program. As the welding program becomes more complex, the controller must include more electrical circuits. A typical program for gas metal arc welding (Figure 12-54) can also be used for flux-cored arc welding or submerged arc welding. The top three lines represent welding current (or wire feed speed) and arc voltage. The next two lines represent auxiliary activities shielding gas and cooling water flow. The bottom line represents travel or relative motion.

At the cycle start point, the operation begins and the specific activities occur. First is preflow of shielding gas and flow of cooling water. After a preset time period the main contactor closes. The arc starts and the electrode wire feed begins. Single-axis travel, rotary or linear, begins at this point or after a preset delay. Travel occurs until the weld is completed but may end at different points, depending on the welding program. The travel or motion control circuit includes a motor speed control circuit. When the weld is completed, there is time for crater fill and time for burnback prior to terminating the weld. The welding circuit contactor will open, the arc stops, but shielding gas continues to flow during a preset postflow period. At the end of this period the shielding gas and water cooling valves close and the welding cycle is

FIGURE 12-54 GMAW welding program.



completed. The cycle can be made to repeat for arc spot welds or for skip welds, or it can only repeat when new pieces are placed in the machine and the cycle reinitiated.

To fully understand a welding program, it is necessary to understand the terms used:

- *Preflow time:* the time between start of shielding gas flow and arc starting (prepurge).
- *Start time:* the time interval prior to weld time during which arc voltage and current reach a preset value greater or less than welding values.
- *Start current:* the current value during the start-time interval.
- *Start voltage:* the arc voltage during the start-time interval.
- *Hot start current:* a very brief current pulse at arc initiation to stabilize the arc quickly.
- *Initial current:* the current after starting but prior to upslope.
- *Weld time:* the time interval from the end of start time or end of upslope to beginning of crater fill time or beginning of downslope.
- *Travel start delay time:* the time interval from arc initiation to the start of work or torch travel.
- *Crater fill time:* the time interval following weld time but prior to burnback time, during which arc voltage or current reach a preset value greater or less than welding values. Weld travel may or may not stop at this point.
- *Crater fill current:* the arc current value during crater fill time.
- *Burnback time:* the time interval at the end of crater fill time to arc outage, during which electrode feed is stopped. Arc voltage and arc length increase and current decreases to zero to prevent electrode from freezing in the weld deposit.
- *Downslope time:* the time during which the current is changed continuously from final taper current or welding current to final current.
- *Upslope time:* the time during which the current changes continuously from initial current value to the welding value.
- *Postflow time:* time interval from current shutoff to shielding gas and/or cooling water shutoff (postpurge).
- *Weld cycle time:* the total time required to complete the series of events involved in making a weld from beginning of preflow to end of postflow.

The controller for running the program above is shown in Figure 12-55. Controllers of this type include meters for arc voltage, for welding current, and sometimes for electrode wire feed speed. It also includes pilot lights for other activities, such as an "arc on" signal to indicate that the arc has been established. This type of controller usually has input voltage compensation and will compensate for welding cable voltage drops, and so on. The controller includes motor speed control circuits, which accurately regulate the wire feed speed motor and the travel speed motor. Time-delay circuits are included whenever a delay period is required. Other activities, such as welding head positioning, fixture clamping, and so on, can be included. A relay controller of this type can only provide one function at a time in a prearranged sequence. Two on/off functions can be simultaneous, and sequenced functions can be in rapid order. This type of controller does not have the capability to ramp or gradually change the welding current during operation. This function is included, however, in controllers for gas tungsten welding and plasma arc welding. Adaptive feedback signals can not be accommodated with this type of controller.

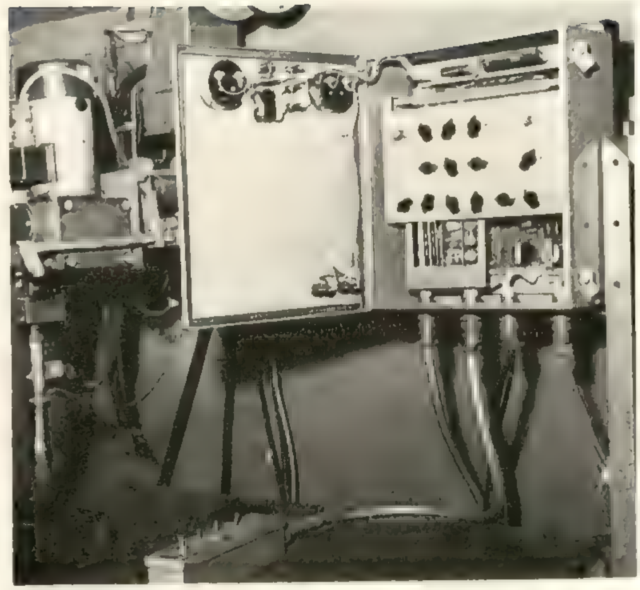


FIGURE 12-55 Welding controller for single axis motion.

Controllers of this type can be preprogrammed to provide specific delays for shielding gas preflow and postflow time, travel start time, crater fill time, and burnback time. Welding current and arc voltage at different levels can be preprogrammed as well as the total weld cycle time. This same type of programmer can be used with limit or proximity switches, to use motion as a control base rather than time.

This controller can control more than one axis of travel motion and it has extra contacts so that it can control other motions, such as fixture clamp, torch advance, and so on. However, it cannot control coordinated or simultaneous motion of two or more axes. Motion must be sequential so that one activity immediately follows the previous one. Coordinated motion requires microprocessor-type controllers.

The electrical diagram of Figure 12-56 is a way of showing relay control logic which performs various tasks automatically based on a sequence of events. A relay is an electrical switch that provides a signal to another circuit when it is activated by a signal generated by another switch. Relays are actuated by any type of signal, which can be a control panel pushbutton, a timer, a limit switch, and so on. Controllers are simple or complicated depending on the number of activities that must be controlled. The one shown is for a semiautomatic wire feeder. A relay logic system requires some operator skill because the control provides the sequencing of operation but still requires the operator to establish parameters and delays and decision-making capabilities to ensure a good-quality weld.

Controls and timers can be standard or precision, depending on the needs of the welding procedure program. Tachometer feedback of wire speed and travel speed motors can be included to provide for more precision and repeatability. The more precise controller ensures consistent high weld quality and repeatability.

The weld control systems described above are relatively simple but are well suited for many, many applications utilizing arc motion and work motion devices. It can be used for standardized and dedicated automatic arc welding machines with not more than two axes of simultaneous (not coordinated) motion.

Robot Controllers

For robotic or automated arc welding systems, a much more complex controller is required. Controllers of this type include a high-speed microprocessor since coordinated, simultaneous, continuous motion of up to eight axes and all welding parameters may be required. As the number of axes increases, the amount of computer capacity must increase.

The machine tool industry introduced numerical controls (NC) years ago. Automatic plasma and flame cutting machines use the same type of controller for directing the path of cutting torches. These are known as point-to-point (PTP) control systems. Points are locations in one plane. For arc welding robots the arc is moved from one point to the next in space. A typical arc welding controller is shown in Figure 12-57. The location of the arc is known as the *tool center point* (TCP). It is the path of the TCP that is programmed and stored in memory. For spot welding, pick and place, and machine loading, point-to-point playback is used. For arc welding, playback of the arc motion is a continuous path in space. The robot controller must be coordinated so that each axis movement begins and ends at the same time. It is the function of the programmer to accept the input of many point locations, relate welding parameters to the path taught, and to store this information in memory, then play it back to execute a welding program. It is beyond the scope of this book to explain its inner workings; however, we will explain how it is used to make welds. The major points of interest are the teach mode, the memory, and playback or execution.

Teaching the Robot

There are at least four methods of teaching or programming a robot controller: manual methods, walk through, lead through, and off-line programming. The manual method is not used for arc welding robots. It is used mainly for pick-and-place robots.

The walk-through method requires the operator to move the torch manually through the desired sequence of movements. Each move is recorded into memory for playback during welding. The welding parameters are controlled at appropriate positions during the weld cycle. This method was used in a few early welding robots.

The lead-through method is the most popular way of programming a robot. The robot welding operator accomplishes this by using a teach pendant (Figure 12-58). By means of the keyboard on the teach pendant, the torch is power driven through the required sequence of motions. In addition, the operator inputs electrode wire feed speed, arc voltage, arc on, counters, output signals, job jump functions, and much more. All of these functions are related to a particular point along the taught path. In this way, if the robot speed is changed, it is not necessary to change the time for certain actions to happen. This means that actions are sequence and position related rather than time related. The travel speed of the torch is independently programmed between specific points by the keyboard.

The path of the arc or tool center point is taught by moving the TCP to a particular point using the teach pendant keyboard. The machine axes locate the torch and the wrist axes control the angle of the torch. There is a control for each drive motor (i.e., one for each axis). When the desired position is reached, it is necessary to record the position by pushing the record button. This same operation is repeated for the next location point, until the complete path is taught. The robot controller must be coordinated to control all the axes simultaneously. The normal arc welding robot has five or six axes (including two or three in the wrist). The controller should have additional capacity to control the axes of positioning equipment. Robot positioners increase overall efficiency and the range of the robot and improve weld accessibility. The robot controller should be able to control the positioner and provides total coordinated motion.

In the playback mode the robot will follow the path between each point according to its interpolation function. Normally, linear interpolation is used, which means that the arc or TCP will move in a straight line between taught points. Circular interpolation means that the arc or TCP will move in a circle. Three points will designate and locate a circle. It is useful for developing a curved

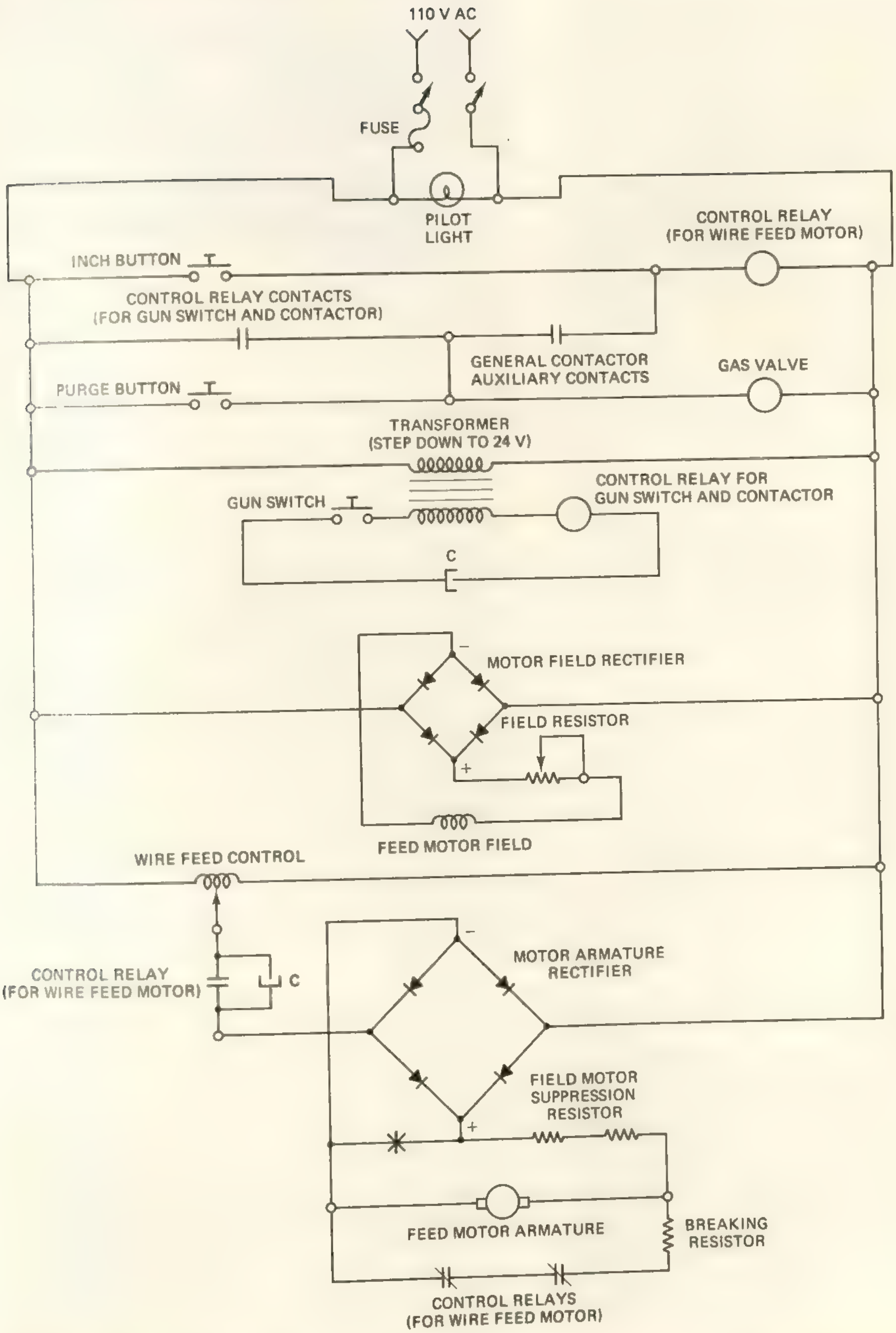


FIGURE 12-56 Electrical diagram for relay control.

FIGURE 12-57 Robot controller.

FIGURE 12-58 Teach pendant.

FIGURE 12-59 Interface panel.

path and reduces the number of points required. The playback mode must be a continuous path.

The controller should allow revision of one taught point without reteaching the entire path. It should allow deletions or additions of taught points. Also, it should allow changes of travel speed or of welding parameters. The operator should be able to check the taught path and welding parameters without welding. The speed of the arc may be set in absolute values or by transverse run time (TRT) or time between points. The above is done in an edit mode so that the taught path can be modified or shortened, speed changed, or welding parameters changed.

An interface (Figure 12-59) is usually required between the robot controller and the welding power source and the electrode wire feeder. Its purpose is to allow the controller to program specific welding current and arc voltage in sequence with the taught path. It also provides subroutines such as weld termination, and so on. The robot controller usually has a number of steps from minimum to maximum to control current and voltage. These steps must be converted to absolute current and voltage values to conform with the program. This is done differently by different welding machines and wire feed controls. The robot controller must program welding parameters in order to have a truly automatic welding system. They must be stored and retrieved the next time the job is run, without the necessity of adjusting the welding equipment.

The robot controller must have a diagnostic system built in to allow a quick check when problems occur. Most robot controllers offer other features, which may be built in or optional. Linear and circular interpolation, mentioned previously, is important. Other features available as options could be:

- Automatic acceleration and deceleration
- Three-dimensional shift
- Simultaneous control of extra axes
- Scale-up and scale-down
- Mirror image
- Software weave

All of these are useful for an arc welding robot. From a welding point of view the software weave is very useful. This allows the robot to manipulate the weld pool like a human welder. It allows a larger weld cross section, better bead contour, and enables the weld to bridge gaps. Different patterns can be programmed, from simple sideway oscillation to triangular patterns. This is taught in three steps. Frequency of the weaving oscillation, amplitude, and dwell at each end are taught. Once

the weaving pattern is taught, welding will continue through changes of path in all planes without reteaching the weaving pattern. Other options include through-the-arc seam tracking and other tracking functions. A thorough study of the robot is necessary to determine and learn what these features include.

Off-line programming involves the preparation of the program on a computer. An appropriate language must be used. The program is entered into the robot memory very quickly. This increases the utilization of the robot, since lead-through teaching ties up the robot during programming. Off-line programming is difficult and requires experienced personnel. It has not yet become popular.

Robot Memory

The amount of memory of the controller is usually indicated by the number of steps and instructions that can be programmed with the number of axes involved. This is often described as having a memory capacity of 2200 steps and 1200 instructions. Memory should have 32K bytes with battery backup. There should be a programming terminal with keyboard and screen displays in addition to the teach pendant.

The controller usually has one or more microprocessors, mircocomputers, or minicomputers. Faster execution, response time to better input/output control, and overall flexibility is possible when two or more processors or computers are used. Controller software which provides all the control features is stored in RAM (random-access memory) in ROM (read-only memory). Memory can be expanded with external cassette tapes, diskettes, or disk drives. External stored information must be read into the RAM prior to execution.

The computer must have communication ports so that it can talk to the overall controller. The robot memory should be selected based on the work to be done.

Weld Execution

Welds can be made only when the power is on all components, electrode wire is installed, and the controller is in the playback or operate mode. The material must be in the fixture and ready. Pushing the start button will initiate the operation. The robot will move the torch to the start point. The welding equipment will begin its cycle of operation (i.e., gas preflow, start the arc, etc.). The robot controller will determine that the arc has started and then start motion. Points along the taught path will initiate other activities programmed. At the end of the taught path the welding equipment will terminate the weld program and the robot controller will determine that the electrode wire has separated from the work. After this the robot will return to its home position, ready for another cycle. At this point the weld should be checked for quality. The program should be checked and edited to improve the weld if necessary and to minimize the air cut path and increase air cut speed. When the weld quality is acceptable and cycle time is at a minimum, it is time to freeze the program and start production.

12-9 SEAM TRACKERS, WELD MONITORING, AND SENSORS

Automatic welding will consistently produce high-quality welds when the weldment piece parts, joint location, joint fitup, and so on, are perfect. An individual using manual or semiautomatic welding can overcome problems of improper fitup, weld joint mislocation, errors in joint fitup, and so on, since a welder is a closed-loop system. To produce good-quality welds with automatic equipment when fitup is improper requires sensing devices and adaptive feedback. Sensing devices and adaptive controls, properly designed, will enable the welding equipment to compensate for joint variations, in real time, and produce the high-quality welds desired. So far attempts to replace the individual by mechanical, electrical, and electronic devices coupled to complex computer-controlled systems has not happened.

To successfully weld without human supervision or intervention, the automated welding apparatus must at least:

- □ Find the weld joint
- □ Follow the weld joint (seam tracking)
- □ Provide root fusion of the weld joint
- □ Provide interpass fusion for multipass weld
- □ Establish the welding technique
- □ Completely fill the joint with reinforcement
- □ Modify and carry out the welding program
- □ Produce a high-quality metallurgical joint

Major components for accomplishing automated welding are sensing devices. There are two basic types, contact or tactile, and noncontact. There are contact-type seam followers, some have been available for many years and are relatively durable. Contact-type sensors are used successfully for many applications but are not suitable for robotic arc welding.

Noncontact-type sensors are much more complex and needed for robotic and automated welding. There are at least three different types of noncontact sensors. One type utilizes physical or technical relationships. Other types utilize arc characteristics while welding and are considered "through-the-arc" systems. The third type utilizes optical or vision means not only to follow the joint but to monitor other conditions as well. Figure 12-60 shows a classification of arc welding sensor systems. The more widely used systems will be described briefly.

I. Contact/tactile (seam tracking)
  A. Mechanicals—roller spring loaded with floating torch
  B. Electromechanical—probe with torch on motorized cross sides
  C. Intermittent contact probe—electromechanical
  D. Electrical-electrode extension probe with complex control

II. Noncontact (for various activities)
  A. Physical characteristics relationship
    1. Acoustical—for arc length control
    2. Capacitance—for proximity control
    3. Eddy current—for seam tracking
    4. Induction—for seam tracking
    5. Infrared radiation—for penetration control
    6. Magnetic—electromagnetic
    7. Ultra sonic—for penetration control and quality control
  B. Through the arc (electrical contact)
    1. Arc length control (arc voltage control)
    2. Oscillation with electrical measurements—GMAW
    3. Oscillation with electrical measurements—GTAW
  C. Optical/visual (image pickup and processes)
    1. Reflected light with photodiode detection
    2. Viewing the welding arc
    3. Viewing the molten weld pool
    4. Viewing the joint ahead of the arc
    5. Laser shadow technique
    6. Laser range-finding technique (rastering)
    7. Optoelectronic
    8. Laser—standard light
    9. Other systems

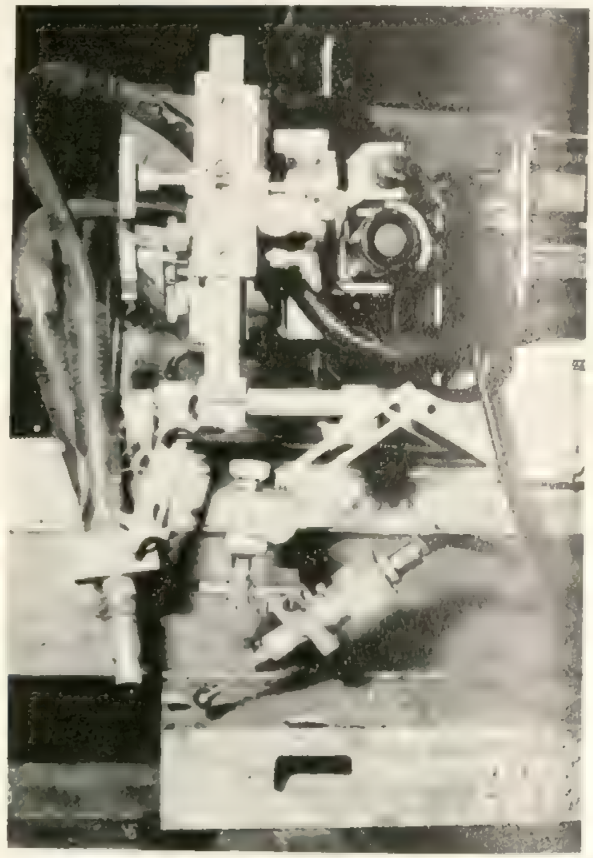
FIGURE 12-60 Types of sensor systems.

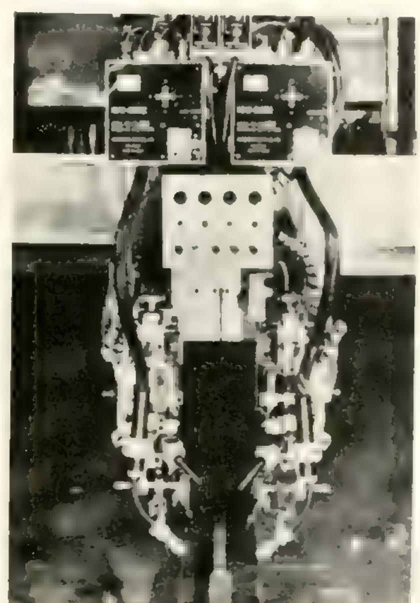
Contact Sensors

Tactile sensors have been used for joint tracking for many years. They range from simple mechanical systems to complex electric mechanical contacting sensors. They are useful for long, straight seams where change of direction is gradual. The simplest contact-type seam tracker is a spring-loaded roller or wheel with a floating welding torch. The roller fits against a reference surface and causes the head to maintain a specific dimensional relationship with the joint. The head will follow the motions generated by the roller. This device is useful for making cambered or shaped beams. It can also be used to maintain a specific distance above the surface of the base metal when welding.

An electromechanical system is more versatile. In this case, a wheel or a stylus probe will contact a surface, which can be the plate surface, the edge of a groove weld, the edge of a fillet weld, or similar, and provide a signal to a control circuit which operates motorized cross slide to move the torch. These are single-axis devices, but can be used for fillet or groove welds. A second axis can be added which provides accurate torch-to-work dimensions. This requires *X-Y* motorized cross slides. The probe and torch are mounted on the carriage. This type of equipment is widely used for long, straight seams with boom and mast manipulators (Figure 12-61). It is also popular for roll welding of pipe with a stationary but floating head over the revolving joint (Figure 12-62). Probes are of different designs. In some cases the end of the probe or stylus is replaceable. It is connected to a pair of switches that provide the signal. The probe must be sufficiently distanced from the arc to prevent spatter buildup. Probes

FIGURE 12-61 Electromechanical contact-type seam tracker.





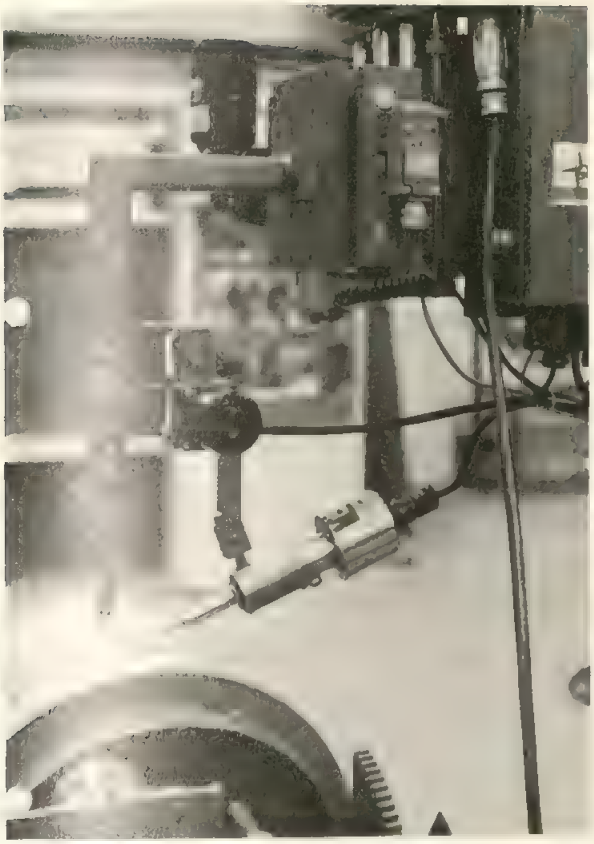
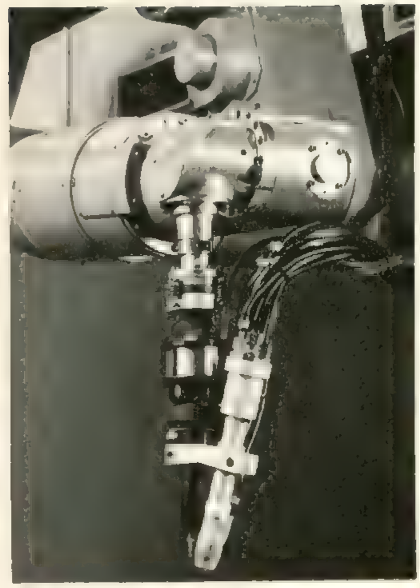


FIGURE 12-62 Electromechanical tracker on pipe weld.



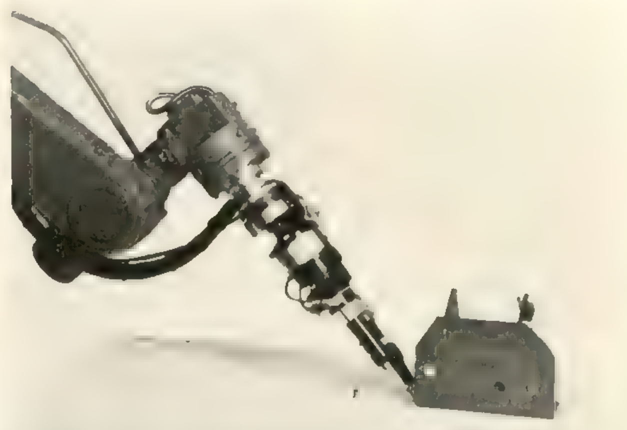


FIGURE 12-63 Intermittent-contact probe system.

wear and must be replaced. A problem with this equipment is tack welds and the start and end of welds. This type of equipment is not suited for robotic arc welding.

A special intermittent contact seam follower is used for robotic arc welding (Figure 12-63). This device is attached to the torch. It is different in that the probe does not touch the work constantly. By means of a pneumatic vibrator the probe will intermittently touch the work about four to five times each second. This eliminates the drag problem associated with the normal probe. This device can be used for fillet welds and lap joints with a minimum material thickness of $\frac{1}{16}$ in. (1.6 mm). This unit feeds signals to the robot control system that controls motion of the torch. It will also search for the beginning of the weld. The search function and the changed path is stored in the robot memory. It will maintain a constant torch-to-work distance as well as following the joint. This device will take care of gradual changes of direction but cannot accommodate a sharp 90° turn.

The problem with systems that use a mechanical probe or wheel is the distance from the arc to the sensing location. If the distance is too great, deviations can occur. If the distance is too short, the arc will interfere with the probe and cause rapid wear and deterioration. The other problem is the inability of these systems to accommodate abrupt changes of direction at welding speeds.

A different type of touch system is employed in conjunction with through-the-arc tracking system. This system utilizes the electrode wire, which protrudes slightly beyond the current pickup tip, as the contact. The electrode wire is programmed to move and touch the work surface and different points within the joint to determine the start location of the weld and the end of the joint. This system can also be programmed to measure the weld geometry and establish the size of the weld groove. It utilizes a complex motion system, and works well on a jointed arm robot. The system is computer driven. It may utilize an expert system and a memory. It is capable of sensing the joint path in three dimensions and storing it in memory. The calculation of the weld joint detail in connection with the expert data bank will establish new welding procedures and will modify welding parameters. The contact is established by using a voltage on the electrode wire, and when it contacts the work it provides loca-

tion signals. This system is becoming popular on robotic arc welding systems that employ through-the-arc sensors.

Noncontact Sensor Systems

There are three basic noncontact-type sensor systems: (1) sensor systems, which rely on physical characteristics of materials or energy output relationships; (2) through-the-arc systems, which utilize electrical signals generated in the arc; and (3) optical/vision systems, which attempt to duplicate the human eye.

The principle of the noncontact physical characteristics relationship or energy output type of sensors is converting the changes in physical properties or energy into electrical signals that can be processed to provide signals to the welding controller to initiate specific actions. These are used for different activities, from limit switches to seam tracking.

Acoustical energy is being used to control the arc length of a gas tungsten arc. Normally, the arc voltage is used. The sound energy is linearly proportional to arc voltage. An acoustical waveguide close to the arc leads to a microphone. The signal is amplified, filtered, and rectified and is used to control the torch movement and thus to control the arc length. It is used for pulsed current gas tungsten arc welding.

Capacitance is the property utilized by some proximity switches. The capacity-type limit switch has been used in automatic equipment for years. It can be adjusted for different distances and is also used to detect the presence or absence of material.

Eddy currents are currents set up in the base metal by an adjacent alternating-current field. Eddy currents can be used for seam tracking. The alternating-current field is generated by a coil located close to the base metal. Another coil acts as the pickup and detects the eddy current. Electronic circuitry produces a voltage dependent on the distance from the base metal. The output changes because the joint interrupts the metal surface. The sensor is oscillated across the joint to produce control signals. These signals are processed to give the position of the joint centerline. Different types are required for ferrous metal and for nonferrous metals. Thickness is not a major factor. This system is one of the more popular noncontact seam tracking systems.

Inductance or induced current in the base metal can be detected and measured and used for seam tracking. The sensor contains two coils, which scan the seam and provide signals giving information on the location of the joint. This is similar to the eddy current system. It must be at a given distance above the base metal. The sensor must be placed ahead of the arc due to sensitivity to heat, spatter, and so on.

Infrared radiation can be picked up by different kinds of sensors and is used for penetration control. The infrared sensor is focused on the underside of the weld pool. The sensor looks at the color of the metal under the weld. This system is subjected to surface conditions and exact target location. It is not considered extremely reliable as a penetration control system and has limited applications.

Electromagnetic systems are basically the same as the eddy current and inductance systems. Ultrasonic energy is widely used for nondestructive testing. It is possible to use ultrasound for real-time penetration control of welds. Coupling the transducer to the work is being done with laser beams. All of these noncontact seam tracking systems have deficiencies.

Through-the-Arc Seam Tracking

Through-the-arc seam tracking has many advantages. It is a noncontact system and it does not have accessory items attached to the torch. It is a real-time system that can be used for different types of welds. Monitoring occurs while making the weld. There are several types of through-the-arc systems. They can be used with processes where the metal crosses the arc or does not cross the arc.

The earliest through-the-arc sensing system was the arc length control system for gas tungsten arc and for plasma arc welding. These systems are called *arc voltage control* (AVC) systems; however, *arc length control* (ALC) is a more appropriate name. The arc voltage is monitored and amplified and used as a reference point for a motorized torch holder. A specific voltage is present in the controller which will maintain that voltage (and arc length) in spite of variations in the work or in the travel path. Some arc systems have a starting mechanism whereby when the cold tungsten of the torch touches the work, it initiates the arc and immediately withdraws to the preset voltage. Arc length control systems are very reliable and have been used successfully for many years.

The major interest of through-the-arc systems is for seam tracking, with gas metal arc and gas tungsten arc welding. The principle of operation is based on oscillating or weaving the welding torch and monitoring the arc voltage and or welding current at each end of the oscillation. Mechanical oscillation or movement is used; magnetic oscillation is used for GTAW but not for gas metal arc welding. It is used for fillet welds or for V-groove welds. Figure 12-64 shows the principle of operation. Control circuits measure the voltage and or current, and references the left-hand value and the right-hand value to make them equal. The control circuit moves the torch to the center point between the two equal low-voltage or low-current points. This automatically adjusts the actual path from the taught path. This system also has a corner recognition mode which allows tracking around a 90° change of direction. The unit is capable of sensing the joint path in three dimensions. It can be used with all modes of metal transfer. Welding speeds of up to 40 in./min can be attained. Weave amplitude can be

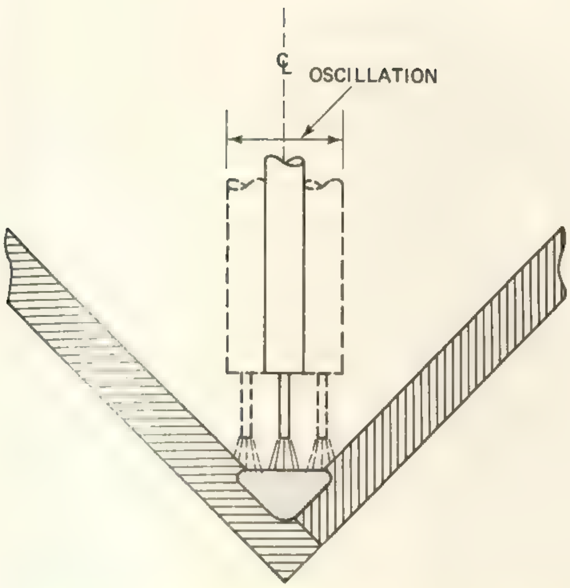


FIGURE 12-64 Through-the-arc guidance system.

from ⅛ to 1 in., and the frequency is from 1 to 4½ Hz. The controls for this system must be integrated into the controls of the robot or automated welding system.

This system is often coupled with the electrical contact system mentioned above, where the electrode wire is used to find and measure the weld joint. The final pass of a groove weld is attained by using the previous passes to establish the torch path in memory. The final or cap pass is made in the correct location.

A similar system can be used with gas tungsten arc welding. Mechanical or magnetic oscillation is employed and the arc voltage is sensed at the end of each oscillation. When the arc length becomes shorter at the end of the oscillation stroke, the stroke is reversed. By equalizing the signals at each end of the oscillation, the torch will follow the centerline of the joint. This is used for groove welding, and with the memory circuit the final pass is made in the correct location.

If the opening or gap in the groove weld is excessive, the machine can be programmed to select a different procedure from the memory bank and make alternate layers for each layer rather than a single pass.

Optical-Visual Sensor Systems

An analysis of manual welding operations reveals that the welder derives the bulk of the information required to make a good-quality weld through vision. This indicates that optical-visual systems have the most potential for providing feedback signals to provide fully automated arc welding. The optical-visual systems do more than follow the seam. They find the seam and identify and define the joint detail so that parameters can be adjusted by means of an expert data base to produce a good-quality weld. Optical-vision systems operate in real time and are extremely fast.

Development of optical-vision systems faces many problems. They must overcome the problem of viewing different colors and surfaces—bright, rusty, smooth, rough, and so on—which tends to confuse the sensor. They also have the problem of picking up a very small joint. In thin materials the joint separation is minimal and scratches on the surface may be more distinctive than the joint. The arc is a very hostile environment. It operates at a high temperature and it produces smoke and airborne contaminants, weld spatter and fumes, acoustical and electrical noise, magnetic interferences, and a very bright light. Since it operates with different modes of metal transfer, from smooth to erratic, the bright arc light varies in intensity and in wavelength.

Tremendous progress has recently been made in the development of optical-visual monitoring systems. Many different systems have been developed and many are operating successfully. One universal system cannot be applied to all robotic or automated welding applications. Different systems are designed for particular applications where they operate successfully.

An optical-visual sensing system consists of several parts (Figure 12-65):

- ☐ The image to be viewed
- ☐ The image pickup method
- ☐ The image display system
- ☐ The image processing system
- ☐ The adaptive control system
- ☐ The expert data bank

The image to be viewed can be the weld joint ahead of the arc, the arc itself, the weld pool under and behind the arc, or the light generated by the arc. The image selected is important since it relates to the viewing area and how it is lighted.

The method of picking up the image can be done in different ways, by means of a TV camera or by means of photodiodes arranged in a linear or matrix array. This affects the image display and processing system. In addition to the method of picking up the image, it is important to determine whether one or two images are required. In some cases triangulation of images is used to provide exact location. Another relates to the location of the pickup, whether it is close to the arc or at a distance. Too much apparatus attached to the welding torch will be overly cumbersome. This will cause rapid deterioration due to arc temperature and radiation. Fiber optics can be used to transmit the image to a remote camera. The angle of viewing relates to the image processing method. Image pickup through the torch has been used for gas tungsten and gas metal arc welding.

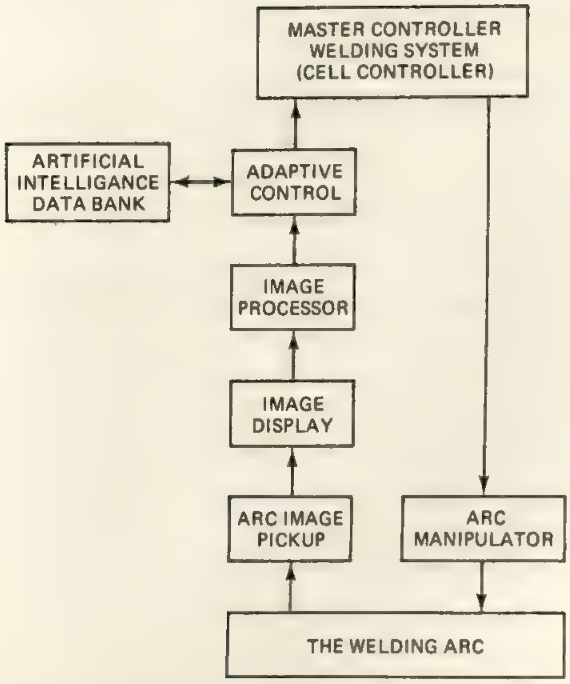


FIGURE 12-65 **Block diagram of visual guidance system.**

Enhanced Image The image should be enhanced for better visibility. One method is the use of structured light. This is usually patterns of bright and no light which can be directed from an oblique angle. Structured light can be visible light or laser light. Laser light has many advantages due to its monochromatic character and its focusing abilities. In addition, by using filters the incident arc light can be filtered out, which simplifies processing. If structured light from one point is used, it is sometimes supplemented by a beam from another direction. This is used for triangulation for precise positioning.

Image Processing The processing of the image from the pickup device must be done to provide a display. Digitizing the image has certain advantages and disadvantages.

Image Display System The most common image display is the cathode ray tube or TV screen display. This is used during the research and development phase, but possibly can be eliminated in the true automated visual system. The image analysis system requires the use of microprocessors with high-speed capabilities. It also requires an extremely complex program to analyze all data received and put them into a useful form so that they can be used to make real-time changes based on variations in the weld.

Adaptive Control System This is the interface between the image analysis system and the controller. It relies on a data base of an expert system to provide weld parameters when conditions change. The complete system will provide the necessary input and permit closing the loop to produce the perfect weld.

Each optical-vision system has advantages and disadvantages. Certain systems are applicable to some applications and others to different applications. The following is a brief list of the systems in use:

- Reflected light with photodiode pickup methods
- Viewing the welding arc with a TV camera
- Viewing the molten weld pool either through the torch or adjacent to the torch
- Viewing the joint ahead of the arc
- The use of laser shadow technique
- Laser range-finding techniques (rastering)
- Two laser-structured light systems with camera pickup
- Other systems

The perfection of optical-visual sensing systems is the objective of many researchers throughout the world. It is expected that within the next decade there will be optical-visual systems for many automated arc welding application.

Sensor Future Developments

To have true automated welding—the unmanned factory—noncontact seam tracking and welding parameter control are necessary. Since the human welder relies mainly on visual information to make a weld, the optic-vision systems have the most likelihood of success. The larger number of factors and variables which have to be monitored in arc welding makes the development of a general-purpose sensing system unlikely. Different types of applications-oriented systems will be developed and perfected, and will be used with automated and robotic arc welding systems for specific applications.

12-10 REMOTE WELDING

Remote welding is automatic welding since the welding is done without the presence of a human welding operator. The operator may be a short distance from the welding operation, but could be far away. Monitoring and adjustments may be done while welding by remote controls.

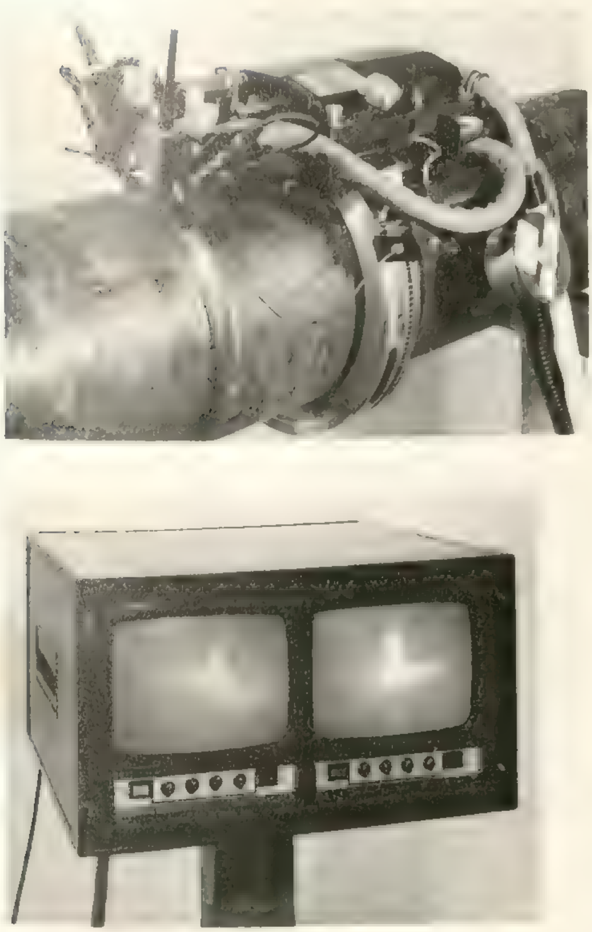
Remote welding is often done for maintenance operations where each weld is different. Remote welding is performed where humans cannot be present because of a hostile atmosphere, such as a high level of radioactivity. A hostile atmosphere requires special protective equipment for the welder, which seriously hampers visibility and flexibility. Radiation greatly reduces the

time that a person can work and allows time only for setting up the equipment.

A common maintenance problem in a nuclear power plant is the repair of heat exchangers when several tubes become defective. The solution is to plug the faulty tube at both ends of the heat exchanger. This is accomplished, as a remote welding operation, using a modified orbital arc welding head. A special plug with a flange is inserted into each end of the tube and the periphery of the flange is welded to the tube sheet. The flange on the plug provides metal to be welded and also covers the leak path. A blind hole in the plug is used to mount the spindle of the orbital head. When the plug is seated into the end of the tube, the machine is started and performs its normal welding operation.

Pipe welds are made remotely in radioactive atmospheres. In this case the pipe joints are properly prepared and aligned. The pipe welding head is attached to the joint by personnel who can work in the radioactive environment for only a short time. The power source and operator control pendant are remote from the welding operation and shielded from radioactivity. Remote welds are made in pipe and tubing, as they would be made with the equipment under normal conditions. To observe the weld being made, a TV camera is mounted on the welding head and monitored remotely. Remote adjustments can be made if required. Figure 12-66 shows equipment of this type in operation.

FIGURE 12-66 TV viewing remote welding.

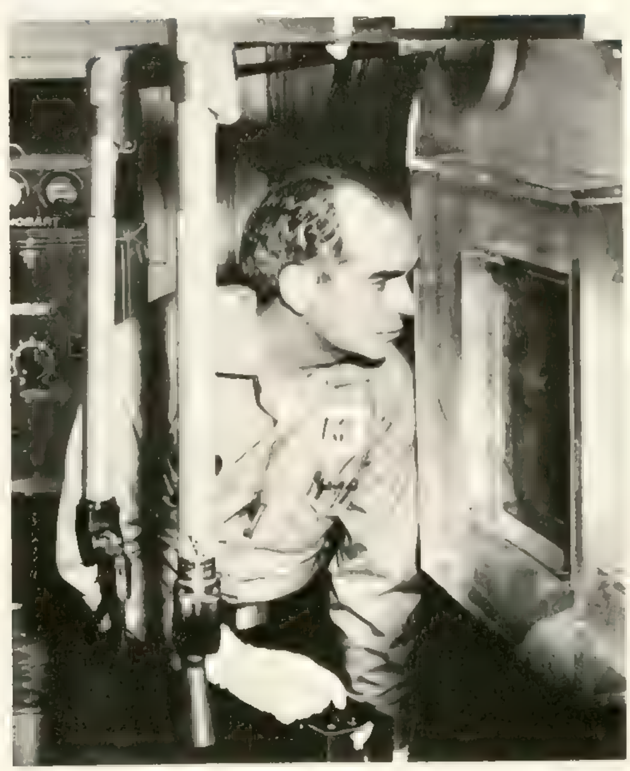


The more difficult jobs are the one-of-a-kind type, where standard equipment cannot be used. The ingenuity of the personnel and the use of gadgetry and special welding equipment is a must. More and more of this type of work is being done as repair welding in radioactive hot areas increases.

Remote cutting using thermal processes is also done. The plasma arc cutting process is used for remote preparation in a radioactive atmosphere. Another requirement is the necessity to cut under water for certain maintenance operations. This is used when the area is flooded, to improve radioactivity shielding.

The nuclear industry uses remote welding for sealing radioactive material in metal containers. Remote weld sealing of spent fuel elements is also performed. This is done by specialized equipment. These involve ingenuity, mechanical gadgetry, and sound knowledge of joining processes and problems that are encountered in the nuclear industry. Figure 12-67 shows an operator monitoring a welding operation inside a heavily shielded hot cell. The welding operation remote movement and adjustment equipment is shown in Figure 12-68.

FIGURE 12-67 Remote welding operation.



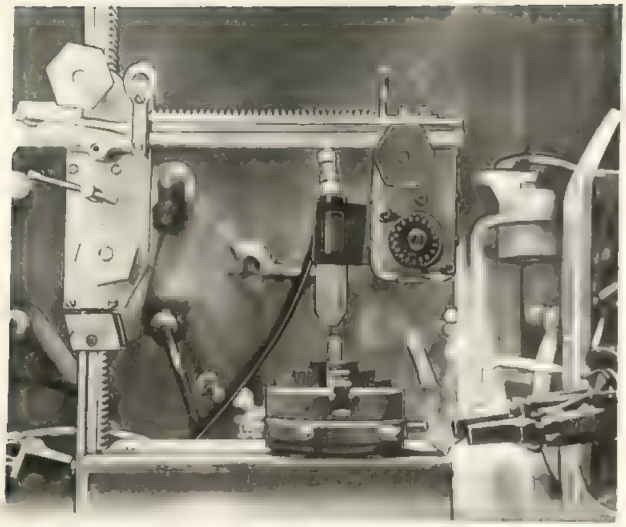


FIGURE 12-68 **Remote welding.**

12-11 TOOLING, FIXTURES, OR WORK-HOLDING EQUIPMENT

A welding fixture or work-holding device is customized for each and every weldment. The welding fixture is a device that holds the component parts of a weldment in the correct location for welding. Fixtures are used when there is sufficient volume of production of similar parts to justify their cost, or if there is need for extreme dimensional accuracy. Automatic arc welding systems, including robotic systems, dedicated automatic machines, standardized automatic machines, and flexible automated systems, require a fixture to locate and hold the parts of the weldment in their proper location for the welding operation.

There are three basic types of welding fixtures:

1. Fixtures for tack welding only the parts together
2. Fixtures for holding the parts of the weldment during the entire welding cycle
3. Fixtures attached to positioning equipment that hold the weldment so that it can be moved for the optimum welding position

The fixture should be strong enough to hold the parts of the weldment in proper location without distortion from the weight of the parts. Fixtures should be sufficiently strong to withstand the distortion of welding. They must be strong enough to withstand normal wear and abuse. Fixtures must locate the component parts in their proper relationship and allow for preparation tolerances of each piece. Fixtures should be designed so that the parts can be easily loaded and held in place. Fixtures should also be designed to allow access for welding with the torch. Finally, fixtures must be designed so that the completed weldment with weld distortion can easily be removed.

The clamping of the parts of the weldment requires special attention. This involves location points and clamping devices. Locating points should be at or near surfaces where machine finishing may be specified. Clamping devices can be manual toggle clamps, screw-threaded clamps operated with power wrenches, or air- or hydraulic-powered clamps. Clamping devices must be positioned so that they do not introduce distortion or deflection into the parts. They must also be strong enough to withstand normal loads and the distortion stresses of welding. The clamps should be located so that they do not interfere with the welding operations. Clamps and location points should be protected from weld spatter.

Welding fixtures may be placed on positioners or other work motion devices. This is done to allow welding in the most economical position. They must be designed for maximum productivity so that they can maximize arc welding time and minimize loading and unloading time. The time for loading and unloading the finished weldment should be less than the welding time.

An efficient fixture will allow unattended welding with automatic welding systems. This allows the operator to load and unload another fixture at the same or at an adjacent workstation. This ensures maximum productivity and will allow quick recovery of the cost of the fixture. It is possible to approach 100% arc time on a properly designed and operating fixture. The other cost savings is the reduced time when using the fixture versus setting up weldments from a blueprint.

There are situations where two fixtures are required for the same weldment, one for tack welding and one for finished welding. The tack welding fixture must accurately locate all pieces, whereas the welding fixture would hold the weldment to a work motion device. These have different requirements and must be designed for their intended use. The design of fixtures is based on the foregoing factors, but it must be tempered with experience gained from making and using fixtures that are successful and economical.

Fixtures are often subcontracted or purchased from a fixture builder or system company. The fixture builder or designer should be selected based on experience of building similar types of fixtures. Responsibility must be established and accepted. There must be complete understanding of the entire project by the fixture user and the fixture producer. This is done by having a meeting attended by the weldment designers, the welding production department, and the fixture designer, or producer. It is necessary to agree on the productivity expected from the fixture, which would include welding time cycle, load time, unloading time, the annual quantity required, and the production lot size, that is, reach an agreement with

all concerned in order to obtain a good-quality fixture at a reasonable price. Written specifications are often used.

It is necessary to provide information concerning the weldment and its weight and size. If possible, show the exact weldment or a similar weldment to the fixture designer. It is necessary to agree on the dimensional tolerances that will be permitted. Show the dimensions and indicate which are critical and which are not. This allows the designer to determine how every piece part must be located and held, how much distortion can be allowed, how much material is allowed for finish machining, and so on. At the same time, it is worthwhile to review previous fixtures produced by the designer and producer.

The specific welding process to be used must be specified; in addition, the size and type of each weld, the position of welding each joint, what type of work motion device will be used, the work envelope of the equipment or robot that is contemplated, the type of welding gun or torch, and whether multiple pass welds will be required. Groove welds versus fillet welds should also be discussed, and in general, the weld details and the weld quality expected.

It is also desirable to indicate the target budget allowed for the fixture. Welding fixtures are expensive and can represent up to 50% of the total cost of the automatic welding cell. The fixture designer and producer should be able to provide an estimate of the cost of the fixture. Specifications should be understood and agreed to by all parties. Also, it is worthwhile to enter into a design-and-build contract between the parties. This would identify the fixture and weldment and finalize the specifications. The preliminary design should be reviewed and approved by the user. The fixture should then be manufactured and proven. This is done by making weldments with the mechanized equipment, and the resultant weldment must meet the specifications.

In view of the above, particularly on complex welding fixtures, complete trust must be established and responsibility accepted. Both parties must be satisfied. As the weldments become more complex, the fixture becomes more complex, and the cost goes up accordingly. Weld fixtures or work-holding devices should be designed and built by people with experience. Properly used, fixtures will pay for themselves quickly.

In contrast to the above, simple work-holding devices can be made quickly and will pay back after being used for one or two batch production runs. Often, the fixture is built around a finished weldment. Assuming that the weldment is dimensionally accurate, the parts produced in the fixture will be accurate. Fixtures used for manual welding can often be upgraded for automatic use. They must be properly identified, stored, and called up again for the next production run of the same part. This keeps the automatic welding system running at full capacity, pays off quickly, and produces good-quality weldments.

QUESTIONS

12-1. What are the advantages of automatic arc welding?

12-2. Explain the man–machine relationship in arc welding.

12-3. What is an arc motion device? Name different types.

12-4. What is a work motion device? Name different types.

12-5. Discuss standardized arc welding machines. Name different types.

12-6. What is a dedicated automatic arc welding machine?

12-7. What was the product welded on the first dedicated arc welding machine?

12-8. What is lot size? What is the difference between job shop, batch, and mass production?

12-9. What machine provides for flexible manufacturing of weldments?

12-10. What is a robot? Define a robot.

12-11. What are the popular types of robots?

12-12. What is a popular application for robotic spot welding?

12-13. What is the robot work envelope?

12-14. How many body axes does a jointed robot have?

12-15. How many wrist axes can a robot have?

12-16. Discuss coordinated motion in a robot and in a robot and positioner.

12-17. What types of products can be welded on a robot? Give examples.

12-18. What is the disadvantage of a touch-type seam follower?

12-19. Explain how a through-the-arc sensor works.

12-20. Why is remote welding employed? Where is it used?

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13

Filler Metals for Welding

OUTLINE

13-1 TYPES OF WELDING CONSUMABLES

There are many types of materials used to produce welds. These welding materials are generally categorized under the term **filler metals**, defined as "the metal to be added in making a welded, brazed, or soldered joint." The filler metals are used or consumed and become a part of the finished weld. The definition has been expanded and now includes electrodes normally considered nonconsumable such as tungsten and carbon electrodes, fluxes for brazing, submerged arc welding, electroslag welding, and so on. The term *filler metal* does not include electrodes used for resistance welding, nor does it include the studs involved in stud welding.

The American Welding Society has issued 31 specifications covering filler materials (Figure 13-1). This figure also shows the welding process for which each specification is intended.[1] These specifications are periodically updated and a two-digit suffix indicating the year issued is added to the specification number. Additional specifications are added from time to time.

Most of the industrial countries issue filler metal specifications. The national specifications do not exactly correspond with one another as far as types of filler metals covered. A correlation of national filler metal specifications is shown in Figure 13-2.

AWS Specification[a]	Specifications Title	For Process Shown					
		OAW	SMAW	GTAW[b]	GMAW	SAW	Other
A5.1	Carbon steel covered arc welding electrodes		X				
A5.2	Iron and steel gas welding rods	X					
A5.3	Aluminum and aluminum alloy arc welding electrodes		X				
A5.4	Corrosion-resisting chromium and chromium-nickel steel covered welding electrodes		X				
A5.5	Low-alloy steel covered arc welding electrodes		X				
A5.6	Copper and copper alloy covered electrodes		X				
A5.7	Copper and copper alloy welding rods	X		X			PAW
A5.8	Brazing filler metal						BR
A5.9	Corrosion-resisting chromium and chromium-nickel bare and composite metal cored and standard arc welding electrodes and rods			X	X	X	PAW
A5.10	Aluminum and aluminum alloy welding rods and bare electrodes	X		X	X		PAW
A5.11	Nickel and nickel alloy covered welding electrodes		X				
A5.12	Tungsten arc welding electrodes			X			PAW
A5.13	Surfacing welding rods and electrodes	X		X			CAW
A5.14	Nickel and nickel alloy bare welding rods and electrodes	X		X	X	X	PAW
A5.15	Welding rods and covered electrodes for welding cast iron	X	X				CAW
A5.16	Titanium and titanium alloy bare welding rods and electrodes			X	X		PAW
A5.17	Bare carbon steel electrodes and fluxes for submerged-arc welding					X	
A5.18	Carbon steel filler metals for gas shielded arc welding			X	X		PAW
A5.19	Magnesium alloy welding rods and bare electrodes	X		X	X		PAW
A5.20	Carbon steel electrodes for flux cored arc welding						FCAW
A5.21	Composite surfacing welding rods and electrodes	X	X	X			
A5.22	Flux-cored corrosion-resisting chromium and chromium-nickel steel electrodes						FCAW
A5.23	Bare low-alloy steel electrodes and fluxes for submerged arc welding					X	
A5.24	Zirconium and zirconium alloy bare welding rods and electrodes			X	X		PAW
A5.25	Consumables used for electroslag welding of carbon and high-strength low-alloy steels						ES
A5.26	Consumables used for electrogas welding of carbon and high-strength low-alloy steels				X (EG)		FCAW (EG)
A5.27	Copper and copper alloy gas welding rods	X					
A5.28	Low-alloy steel filler metals for gas-shielded arc welding			X	X		PAW
A5.29	Low-Alloy steel flux-cored welding electrodes						FCAW
A5.30	Consumable inserts			X			
A5.31	Fluxes for brazing						BR

[a]AWS filler metal specifications can be obtained from the American Welding Society, Miami, Florida.
[b]If GTAW is shown, the specifications will also apply to PAW even though not stated.

FIGURE 13-1 AWS filler metal specifications and welding processes.

Country Issuing Specification	USA	Canada	Int'l	British	German	Japan	US Military
Filler metal type	AWS	CSA	ISO	BS	DIN	JIS	US-MIL
Covered electrodes—mild steel	A5.1	W48.1	670 R635 547	639 +1719	1913	Z3210 Z3211	E-15599 E-22200
Covered electrodes—low alloy steel	A5.5	W48.3	1045	2493 1719	1913	Z3212	E-22200/1
Covered electrodes—stainless steel	A5.4	W48.2		2926	8556	Z3221	E-13080 E-22200/2A
Covered electrodes—surfacing	A5.13				8555	Z3251	E-19141
Covered electrodes—for cast iron	A5.15		1163		8573	Z3252	
Covered electrodes—aluminum	A5.3			1616	1732		E-15597
Covered electrodes—copper	A5.6				1733		E-13191 E-21659
Covered electrodes—nickel	A5.11				1736		E-21562
Bare—solid—stainless steel	A5.9		1159	2901	8556	Z3321	E-19933 R-5031
Bare—solid—steel	A5.17 A5.18	W48.4		4165 1453	8559	Z3311	E-18193 E-23765
Flux cored—steel	A5.20 A5.23	W48.5					E-24403

FIGURE 13-2 **National specifications for welding electrodes.**

In the United States, the American Welding Society filler metal specifications are the primary ones used by industry. The American Society of Mechanical Engineers in their "Pressure Vessel and Boiler Code" issues filler metal specifications that are identical with the AWS specifications. The numbers are changed slightly; ASME adds the prefix letters SF to the specification number. The U.S. Department of Defense also issues standards for welding filler metals. These are known as MIL specifications and are used for procurement by the government. These specifications are usually in agreement with AWS specifications; however, if a military specification is referenced, it should be consulted.

The Canadian Standards Association issues filler metals specifications which are in general agreement with the AWS specifications. The Canadians have, however, issued additional categories, which are described in detail in the CSA filler metal specifications.

The International Standards Organization (ISO) also issues filler metal specifications. Many of the less industrialized nations utilize specifications of the industrialized countries or ISO standards. The ISO standards are available from the welding or standardization association of each country.

Filler metals can be classified into four basic categories. These are:

1. Covered electrodes
2. Solid (bare) electrode wire or rod
3. Fabricated (tubular or cord) electrode wire
4. Fluxes for welding

The AWS specifications are written in order to provide specific chemical composition of the material and the mechanical properties of the deposited weld metal. The AWS specifications utilize similar methods and testing techniques so that there is consistency between all of the filler metal specifications. The mechanical properties of deposited weld metal are determined based on a standardized welding procedure, in a specified welding joint detail, to produce weld specimens for testing. Specifications also may require other properties such as toughness, quality standards, and, in some cases, standards of porosity. Most specifications include usability factors showing the welding position that the electrode or filler metal is designed for, the type of welding current that should be used, and in the case of covered electrodes, the type of coating is shown. Size and packaging information is also provided.

The American Welding Society does not test or approve filler metals. The society provides the specifications, which are voluntary conformance standards. It is the manufacturer of the filler material who guarantees that their product conforms to a specific AWS specification and classification. AWS provides charts showing comparison of brand names.[1]

Weld Metal Certifications

For special applications, filler metals are tested and certified to be in conformance with a specific specification. In some cases filler metals to be used for ships, nuclear reactors, vessels, highway bridges, and certain military

products require certification. For military construction, approvals are granted when the specific electrodes are in conformance with the applicable military specification. Tests of this type are usually witnessed by a government inspector. Approved products are then placed on a qualified products list (QPL).

Approval of filler metals for ship construction is similar. A classification society, such as the American Bureau of Shipping, requires that one of their representatives, called a surveyor, witness the welding of test plates based on electrodes selected at random. The surveyor also witnesses the testing of the weld specimens. Classification societies also have special mechanical property requirements and these usually include low-temperature impact data. Approvals are granted for different filler materials based on strength and impact requirements and for welding different classes of steels for ships. The classification society publishes lists of approved electrodes and filler metals manufactured by different companies. Retention of the filler metals on the approved list may be subject to annual tests. Filler metal approvals include covered electrodes, submerged arc electrode wire with flux combinations, and flux-cored arc welding electrodes with gas combinations.

Certification is handled differently from approvals. Certification is required for nuclear work and for certain types of military work. In these cases, a specific batch of electrodes or heat of wire made at one time is tested in accordance with a specification which may be either AWS or MIL specification. The test results must then be certified by the manufacturer and provided to the user. A certification is used only for the specific batch or lot of filler materials made at one time and covered by the test result data. In many cases, the user must previously have approved the manufacturer prior to using filler materials produced by that manufacturer. This will require an audit by the user of the manufacturer to make sure that uniform quality manufacturing procedures are maintained and that quality control procedures provide for strict control and traceability of materials used in the manufacturer of the filler material. After the producer has been approved, the certification test may still be required. Traceability of all items is necessary so that the user can provide traceability of all materials used to manufacture the reactor.

Filler metal specifications are of immense value to both producer and user. They allow the user to select the proper filler material to be used to manufacture all types of products. Specifications assure the user that the deposited weld metal, when normally applied, will provide the strength levels indicated by the specification and classification. Specifications are of value to the producer, since they provide standardization of testing methods and procedures and also since they provide categories and classifications to meet the needs of most users.

13-2 COVERED ELECTRODES

The covered electrode is the most popular type of filler metal used in arc welding. The identification of electrode types, the selection of electrodes for specific applications, and the usability of covered electrodes has been discussed in Section 6-3.

The composition of the covering on the electrode determines the usability of the electrode, the composition of the deposited weld metal, and the specification of the electrode. The composition of coatings on covered arc welding electrodes has been surrounded in mystery and little information has been published. The formulation of electrode coatings is very complex and while it is not an exact science it is based on well-established principles of metallurgy, chemistry, and physics, tempered with experience.

The original purpose of the coating was to shield the arc from the oxygen and nitrogen in the atmosphere. It was subsequently found that ionizing agents could be added to the coating which helped stabilize the arc and made electrodes suitable for alternating current welding. It was found that silicates and metal oxides helped form slag, which would improve the weld bead shape because of the reaction at the surface of the weld metal. The deposited weld metal was further refined and its quality improved by the addition of deoxidizers in the coating. In addition, alloying elements were added to improve the strength and provide specific weld metal deposit composition. Finally, iron powder has been added to the coating to improve the deposition rate.

An electrode coating is designed to provide as many as possible of the following desirable characteristics. Some of these characteristics may be incompatible and therefore compromises and balances must be provided and designed into the coating. These desirable-characteristics are:

1. Specific composition of the deposited weld metal
2. Specific mechanical properties of the deposited weld metal
3. Elimination of weld metal porosity
4. Elimination of weld metal cracking
5. Desirable weld deposit contour
6. Desirable weld metal surface finish (i.e., smooth, with even edges)
7. Elimination of undercut adjacent to the weld
8. Minimum spatter adjacent to the weld
9. Ease of manipulation to control slag in all positions
10. Stable welding arc
11. Penetration control (i.e., deep or shallow)
12. Initial immediate arc striking and restriking capabilities

13. High rate of metal deposition
14. Elimination of noxious odors and fumes
15. Reduced tendency of the coating to pick up moisture when in storage
16. Reduced electrode overheating during use
17. Strong, tough, durable coating
18. Easy slag removal
19. Will ship well and store indefinitely

These requirements must be achieved at the minimum possible cost. In addition, the formulation must be manufacturable with conventional extrusion equipment at high production rates. No single electrode type will meet all of the foregoing requirements, and there is no one single "universal electrode." Instead, there is a variety of electrode types each having certain desirable characteristics.

The coatings of electrodes for welding mild and low alloy steels may have from 6 to 12 ingredients, such as:

- *Cellulose:* to provide a gaseous shield with a reducing agent. The gas shield surrounding the arc is produced by the disintegration of cellulose.
- *Metal carbonates:* to adjust the basicity of the slag and to provide a reducing atmosphere.
- *Titanium dioxide:* to help form a highly fluid but quick-freezing slag. It will also provide ionization for the arc.
- *Ferromanganese and ferrosilicon:* to help deoxidize the molten weld metal and to supplement the manganese content and silicon content of the deposited weld metal.
- *Clays and gums:* to provide elasticity for extruding the plastic coating material and to help provide strength to the coating.
- *Calcium fluoride:* to provide shielding gas to protect the arc, adjust the basicity of the slag, and provide fluidity and solubility of the metal oxides.
- *Mineral silicates:* to provide slag and give strength to the electrode covering.
- *Alloying metals:* These include nickel, molybdenum, chromium, and so on, to provide alloy content to the deposited weld metal.
- *Iron or manganese oxide:* to adjust the fluidity and properties of the slag. In small amounts iron oxide helps stabilize the arc.
- *Iron powder:* to increase the productivity by providing additional metal to be deposited in the weld.

By using combinations and different amounts of these constituents it is possible to provide an infinite variety of electrode coatings. The binder used for most electrode coatings is sodium silicate, which will chemically combine and harden to provide a tough, strong coating. The design of the coating provides the proper balance to give the electrode specific usability characteristics and to provide specific weld deposit chemistry and properties. In general, the different makes of electrodes that meet a particular classification have somewhat similar compositions. The principal types of electrode coatings for mild steel and low-alloy electrodes are described in the following paragraphs.

Cellulose/Sodium (EXX10) Electrodes of this type have up to 30% cellulosic material in the form of wood flour, or reprocessed paper. The gas shield will contain CO_2 and hydrogen, which are reducing agents. These gases tend to produce a digging arc that produces deep penetration. The weld deposit is somewhat rough and the spatter is at a higher level than other electrodes. It does provide extremely good mechanical properties particularly after aging. This is one of the earliest types of electrodes developed and is widely used for cross-country pipelines using the downhill welding technique. It is normally used with direct current with the electrode positive (reverse polarity).

Cellulose/Potassium (EXX11) This electrode is very similar to the cellulose–sodium electrode with the exception that more potassium is used than sodium. This provides ionization of the arc and makes the electrode suitable for welding with alternating current. The arc action, the penetration, and the weld results are very similar.

In both E6010 and E6011 electrodes, small amounts of iron powder may be added. This will assist in arc stabilization and will also slightly increase the deposition rate.

Rutile/Sodium (EXX12) When the rutile or titanium dioxide content is relatively high with respect to the other constituents, the electrode will be especially appealing to the welder. Electrodes with this coating have a quiet arc, an easily controlled slag, and a low level of spatter. The weld deposit will have a smooth surface and the penetration will be less than with the cellulose electrode. The weld metal properties will be slightly lower than the cellulosic types. This type of electrode provides a fairly high rate of deposition. It has a relatively low arc voltage and can be used on alternating current or on dc with electrode negative (straight polarity).

Rutile/Potassium (EXX13) This electrode coating is very similar to the rutile-sodium type except that potassium is used to provide for arc ionization which makes it more suitable for welding with alternating current. It can also be used with direct current with either polarity. It produces a very quiet smooth running arc.

Rutile/Iron Powder (EXXX4) This coating is very similar to the rutile coatings mentioned above except that

iron powder is added. If the addition of iron powder is in the 25 to 40% category, it would result in an EXX14-type electrode. If the iron powder addition is 50% or higher it will result in an EXX24-type electrode. With the smaller amount of iron powder the electrode can be used in all positions, whereas with the high percentage of iron powder it can be used only in the flat position or for making horizontal fillet welds. In both cases the deposition rate is increased based on the amount of iron powder included in the coating.

Low Hydrogen/Sodium (EXXX5) Coatings that contain a high proportion of calcium carbonate or calcium fluoride are termed low hydrogen and in some cases called lime ferritic or basic-type electrodes. In this class of coating, cellulose, clays, and other minerals that contain combined water are not used. This is to ensure the lowest possible hydrogen content in the arc atmosphere. In addition, these electrode coatings are baked at a higher temperature. The low-hydrogen electrode family has superior weld metal properties. They provide the highest ductility of any of the deposits. These electrodes have a medium arc with medium or moderate penetration. They have a medium speed of deposition but do require special welder technique for best results. Low-hydrogen electrodes must be stored under controlled conditions. This type is normally used with direct current with electrode positive (reverse polarity).

Low Hydrogen/Potassium (EXXX6) This type of coating is very similar to the low hydrogen/sodium except for the substitution of potassium for sodium to provide arc ionization. This electrode is used with alternating current and can be used with direct current electrode positive (reverse polarity). It has become considerably more popular than the sodium type. The arc action is smoother but penetration of the two electrodes is very similar.

Low Hydrogen/Iron Powder (EXXX8) The coatings in this class of electrodes are similar to the low-hydrogen type mentioned previously; however, iron powder is added to the electrode, and if it is added in the amount of 35 to 40%, the electrode will be classed as an EXX18. This electrode produces excellent weld metal.

Low Hydrogen/Iron Powder (EXX28) Similar to the EXX18 but with 50% or more iron powder added to the coating. This electrode is usable only in the flat position or for making horizontal fillet welds. The deposition rate is higher than the EXX18.

Low-hydrogen coatings are used for all the higher-alloy electrodes. By additions of specific metals in the coatings these electrodes then become the alloy types, where suffix letters are used to indicate weld metal compositions. Electrodes for welding stainless steel are also of the low-hydrogen type.

Iron Oxide/Sodium (EXX20) Coatings with high iron oxide content produce a weld deposit with voluminous slag, which is rather difficult to control. This coating type produces high-speed deposition, and it provides medium penetration with a low spatter level. The resulting weld has a very smooth finish. The electrode is restricted to the flat position and for making horizontal fillet welds. The deposit weld metal has good weld metal properties. The electrode can be used with ac or direct current with either polarity. This type of electrode was the original "hot rod" type of electrode. It has become less popular because of the iron powder electrodes.

Iron Oxide/Iron Powder (EXX27) This type of electrode is very similar to the iron oxide/sodium type except that 50% or more iron powder is added to the coating. This greatly increases the deposition rate. This type is quickly supplanting the EXX20 type because although it has similar weld metal deposit characteristics, it is more desirable from the welder's point of view, and it can be used with either alternating or direct current of either polarity.

There are many other types of coatings than those mentioned here, most of which are usually combinations of these types but for special applications such as hard surfacing, cast iron welding, and for nonferrous metals.

Manufacturing

Covered arc welding electrodes are manufactured at machine-gun-like speeds. This is necessary to keep up with the use of covered electrodes throughout the world. There are three basic parts of a covered electrode: the core wire, the chemicals and minerals that comprise the coating, and the liquid binder that hardens and holds it all together. The steps required to manufacture a covered electrode are shown in Figure 13-3 which is a flow chart showing each of the major steps involved.

The core wire for mild steel and low-alloy steel electrodes is normally a low-carbon steel having a carbon content of about 0.10% carbon, low manganese and silicon content, and the minimum amount of phosphorus and sulfur. Ingots of this composition are produced at the steel mill; they are hot rolled and reduced in size to billets. These are then taken to a bar mill and rolled into small-diameter rods which range in size from ¼ in. (6.4 mm) to ⅜ in. (9.5 mm) in diameter. This product, which is known as *hot-rolled wire rod*, is then taken to the wire drawing mill and drawn into the appropriate diameters for covered electrodes. After the wire has been drawn to the proper diameter it is straightened and cut to the proper length. The lengths vary according to the size and range from 12 to 14 in. in the United States, and from 200 to 500 mm in length elsewhere.

The coating is made of different chemicals and minerals obtained throughout the world. They are inspected and ground to the proper mesh size. The specific

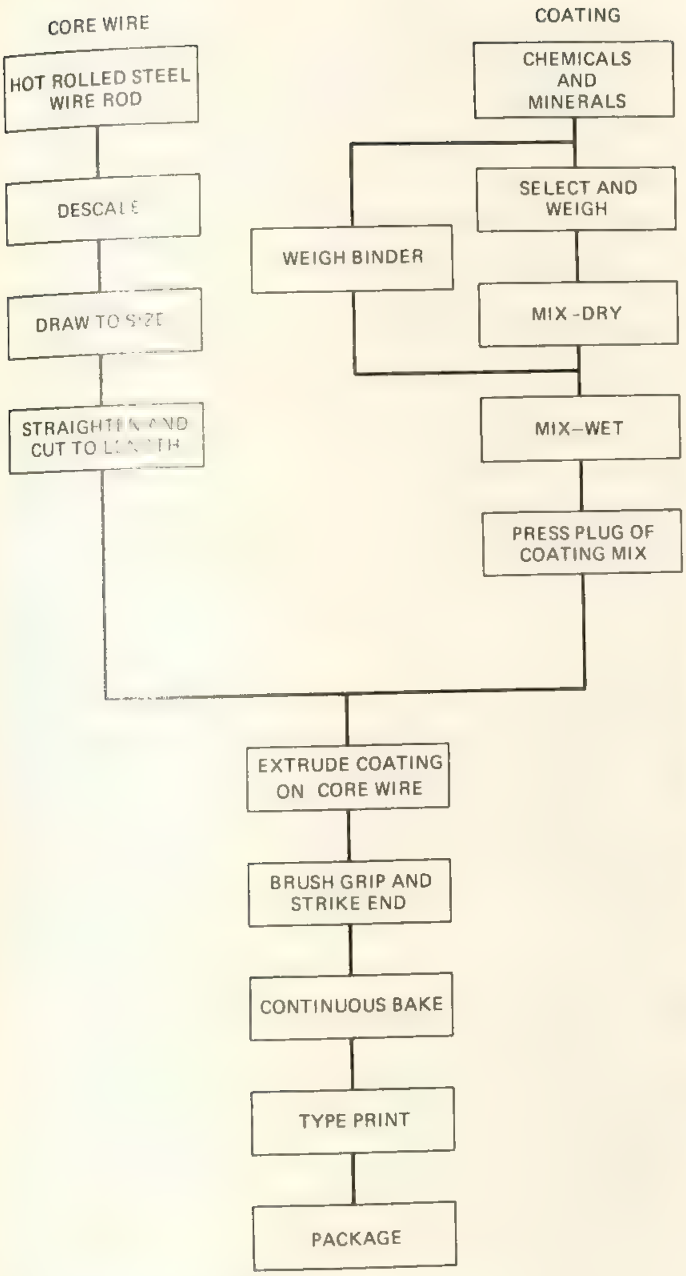


FIGURE 13-3 **Flowchart for manufacturing covered electrodes.**

amount of each chemical is weighed and mixed together in the dry condition. After sufficient dry mixing the proper amounts of liquid, binder, and water are added, and mixing is continued in the wet stage. Mixing is completed when it reaches the proper consistency. This material is then placed in a press, where it is formed into large briquets of moist flux coating material.

The briquets of coating material and the cut and straightened lengths of core wire are brought together at the extrusion press. The cut core wires are fed into the extrusion die by an automatic feeder. Simultaneously, the press feeds flux into a chamber and extrudes the coating onto the core wire as it passes through the chamber. The extrusion die holder must be adjusted with extreme accuracy so that the flux flows uniformly to make it concentric with the core wire. The coated electrode emerges from the die of the extrusion press at a rate of approximately 10 per second. They drop onto a conveyor where power brushes remove a portion of the coating at the grip end and clean the coating from the strike end. The electrodes move on the conveyor into a drying oven for a sufficient length of time for the coating to solidify and toughen. At the exit end of the oven each electrode is individually printed with the AWS classification number and then inspected and placed in boxes and packed for shipment. The entire operation from start to finish is continuous. Figure 13-4 shows the electrodes during the manufacturing operation.

FIGURE 13-4 **Electrodes being manufactured.**

Care, Storage, and Reconditioning of Covered Electrodes

Covered electrodes can be easily damaged. Each electrode should be treated with care prior to its use. Rough handling in shipment or in storage can cause a portion of the coating to crack loose from the core wire and make the electrode unsuitable. Bending most electrode types will cause the coating to break loose from the core wire. The electrode should not be used where the core wire is exposed.

Electrodes may become unusable if they are exposed to moisture for an extended length of time. The coatings on some types of electrodes absorb moisture when exposed to humid atmospheres. Cellulose, rutile, and acid type electrodes are fairly insensitive to moisture and can tolerate quite high moisture content without the risk of porosity in the weld. The coatings of low-hydrogen type electrodes, particularly those of the EXX16 type, pick up moisture quickly when exposed to a high-humidity at-

mosphere. Since these electrodes are dried in a high temperature and a low-moisture atmosphere, they are more sensitive to pickup. Stainless steel electrodes are in this same category.

If electrodes, even in unopened cardboard containers, are left outdoors it is possible that they will pick up moisture due to the change of temperature and humidity from day to night. The moisture is absorbed by the packaging and in turn the moisture is gradually absorbed by the coatings of the electrodes inside the package. Efforts to prohibit this are made by wrapping the electrodes in plastic liners or by using vaporproof or metal containers. These provide additional protection to the electrodes.

Once the container is opened, the electrodes should be stored in heated ovens in accordance with Figure 13-5. Low-hydrogen electrodes must not be stored in ovens that hold electrodes of other classifications. Nothing else should be in ovens that hold low-hydrogen electrodes. Food must not be placed in electrode ovens since the moisture given off during cooking will damage the low-hydrogen coatings.

Damp electrodes are difficult to distinguish by the welder. It is easier to recognize the problem based on storage conditions. It is also easy to recognize the problem by reviewing x-rays of weld metal deposited by damp electrodes. The weld metal will be porous if the coatings are damp. It is sometimes possible to shake three or four low-hydrogen electrodes together and listen to the sound as they rattle against each other. If the electrode coatings are dry or contain only small amounts of moisture, a clear shrill metallic sound will be heard. Damp electrodes have a hollow sound, which is quite different. Experience in testing electrodes in this way will help to distinguish these two different sounds. When welding with an electrode with a damp coating a fierce crackling or explosive sound may be heard. If the electrode is extremely damp, condensed vapor may be seen while welding. If the electrode is not completely consumed, the coating on the remaining part of the electrode will show longitudinal cracks.

Electrodes that are only slightly damp can be heated up by shorting them against the work for a few seconds just before beginning to weld. For reconditioning electrodes, special ovens are available. These are set at specific temperatures for specific types of electrode coatings (Figure 13-5). The baking cycle for reconditioning electrodes should not exceed 4 hours. The heating rate in the oven is not critical. Electrodes can be taken from room temperature and placed in an oven without affecting the properties of the deposited weld metal. The maximum temperature for any low-hydrogen electrode is 800 °F (427 °C). Some ingredients in the coating tend to oxidize if the temperature is raised above this figure. The holding time at the maximum temperature should be at least 30 minutes. This ensures that the electrodes are up to the oven temperature. The cooling rate is not critical; however, reconditioned electrodes should not be

FIGURE 13-5 Storage and reconditioning electrodes.

Electrode Classification	Recommended Storage Unopened Boxes	Recommended Storage Open Boxes	Holding Oven	Reconditioning
E-XX10	Dry @ room temp	Dry @ room temp	Not recommended	Not done
E-XX11	Dry @ room temp	Dry @ room temp	Not recommended	Not done
E-XX12	Dry @ room temp	Dry @ room temp	Not recommended	Not done
E-XX13	Dry @ room temp	Dry @ room temp	Not recommended	Not done
E-XX14	Dry @ room temp	150-200° F	150-200° F	250-300° F 1 Hour
E-XX20	Dry @ room temp	150-200° F	150-200° F	
E-XX24	Dry @ room temp	150-200° F	150-200° F	
E-XX27	Dry @ room temp	150-200° F	150-200° F	
E-60 or 7015	Dry @ room temp	250-450° F	150-200° F	500-600° F 1 Hour
E-60 or 7016	Dry @ room temp	250-450° F	150-200° F	
E-7018	Dry @ room temp	250-450° F	150-200° F	
E-7028	Dry @ room temp	250-450° F	150-200° F	
E-80 & 9015	Dry @ room temp	250-450° F	200-250° F	600-700° F 1 Hour
E-80 & 9016	Dry @ room temp	250-450° F	200-250° F	
E-80 & 9018	Dry @ room temp	250-450° F	200-250° F	
E-90-12015	Dry @ room temp	250-450° F	200-250° F	650-750° F 1 Hour
E-90-12016	Dry @ room temp	250-450° F	200-250° F	
E-90-12018	Dry @ room temp	250-450° F	200-250° F	
E-XXX-15 or 16	Dry @ room temp	250-450° F	150-200° F	450° F 1 Hour
Stainless	Dry @ room temp	250-450° F	150-200° F	

taken from the oven and allowed to cool until the oven has come down to approximately 300 °F (149 °C). Electrodes should not be reconditioned by heating more than three times. Going through the extra heating cycle tends to weaken the silicate binder and the coating will eventually become weak and fragile and will chip off easily.

Electrodes should be stored in a special storeroom with controlled atmosphere. The relative humidity should be maintained at 40% or less. This can be accomplished by sealing the room and installing a dehumidifier.

When low-hydrogen electrodes are issued from the controlled atmosphere storeroom, they should be used within 2 hours. When this cannot be done, individual ovens should be provided for each welder. They can then be left in the heated oven until the electrode is used. All low-hydrogen electrodes not used during a work shift should be returned to the holding oven. For critical work special controls are instituted to maintain dry electrodes.

Electrodes can be damaged by aging. Very old electrodes of most types will have a furry surface on the coating, usually white. This is from the crystallization of the sodium silicate. This surface is normally harmless for mild steel low-hydrogen electrodes. They should not be used for extremely critical work. If iron powder type electrodes are old, rust may form on the iron powder due to moisture absorbed in the coating. If the core wire is rusty, it is possible that too much moisture may have been absorbed in the coating.

Deposition Rates

The different types of electrodes have different deposition rates, as a result of the composition of the coating. The electrodes containing iron powder in the coating have the highest deposition rates. The percentage of iron powder is confusing when comparing electrodes produced in Europe with those produced in the United States. In the United States the percentage of iron powder in a coating is in the range 10 to 50%. This is based on the amount of iron powder in the coating versus the coating weight. This is shown in the formula

$$\%\ \text{iron powder} = \frac{\text{weight of iron powder}}{\text{total weight of coating}} \times 100$$

The percentages mentioned above are related to the requirements of the AWS specifications. The European method of specifying iron powder is based on the weight of deposited weld metal versus the weight of the bare core wire consumed, or

$$\%\ \text{iron powder} = \frac{\text{weight of deposited metal}}{\text{weight of bare core wire}} \times 100$$

Thus if the weight of the deposit were double the weight of the core wire, it would indicate a 200% deposition efficiency even though the amount of the iron powder in coating represented only half of the total deposit. The 30% iron powder formula used in the United States would produce a 100 to 110% deposition efficiency using the European formula. The 50% iron powder electrode figured on U.S. standards would produce an efficiency of approximately 150% using the European formula.

Quality and Defects

Quality control in manufacturing of covered electrodes starts at the point of receiving chemicals and minerals, the binders and the hot rolled wire rod. The chemicals must meet rigid specifications and are checked when they are received. The wire rod, which is checked on a continuous basis, must also meet stringent specifications. Grind sizes of chemicals, cleanliness of mixing containers, and so on, are routinely inspected. The adjustment of the extrusion die to maintain concentricity of the electrodes is checked at each setup. Electrodes are checked after baking for coating concentricity. The surface and structure of the coating is also inspected and each lot is checked by welding to determine that it meets the specifications.

A common complaint of quality of electrodes is *fingernailing*, which is the name given to the burning off of an electrode faster on one side than on the other. The welder assumes that fingernailing means a nonconcentric electrode; however, other factors might create the fingernailing. Fingernailing is most common when using direct current and is more evident with the smaller electrodes, 1/8 in. (3.2 mm) and 5/32 in. (4.0 mm), when used at low currents. This condition can be aggravated if the coating is not concentric with the core wire. This can be checked by removing the coating from the one side of the core wire and measuring the core wire and covering to the other side, and then removing coating on the opposite side of the electrode and measuring the electrode core wire and covering on the other side. Measuring should be done with a micrometer. Normally, electrodes are concentric within 0.002 to 0.003 of an inch (0.05 to 0.07 mm). More often fingernailing results from arc blow, welding current too low, incorrect electrode angle, unbalanced joint preparation, and in some cases, uneven moisture pickup in the coating, which might be greater on one side than the other. A quick check for fingernailing during welding is to stop welding when fingernailing is encountered and rotate the electrode in the holder 180°. Continue to weld and see if fingernailing continues on the same side of the electrode. If it does, the coating is probably off center. If it does not but instead fingernails off the other side, arc blow or one of the other factors mentioned above is the reason. Arc blow is a more frequent cause of fingernailing than off-center electrodes. When welding with lower than normal current fingernailing will appear because there is insufficient arc force to overcome minor arc blow. The other factor is electrode

angle, which again can be checked by revolving the electrode 180° in the holder. Moisture can be checked as mentioned previously.

The welder or the welding supervisor may wish to compare different brands of electrodes. Many electrode manufacturers provide such charts; however, the most complete chart is published by the American Welding Society and is known as the "Filler Metals Comparison Chart."[1]

13-3 SOLID ELECTRODE WIRES

Solid metal wires were first used for oxyfuel gas welding to add filler metal to the joint. These wires or rods were provided in straightened lengths approximately 36 in. (1 m) long. The earliest electrodes for arc welding were also solid and bare, usually of 12 to 14 in. long (300 to 350 mm). Later, solid wire was provided in coils for "bare wire" automatic arc welding and later for submerged arc and electroslag welding. The latest process to use solid bare wire is gas metal arc welding, which uses relatively small diameter electrode wires.

The manufacturer of wire for welding electrodes or rod is essentially the same except that the straighten and cut operation is added for a welding rod. A simplified flowchart of the manufacturing operations for solid mild steel electrode wire is shown in Figure 13-6. The most complex portion is the drawing operation shown partially in Figure 13-7. The drawing of steel wires and nonfer-

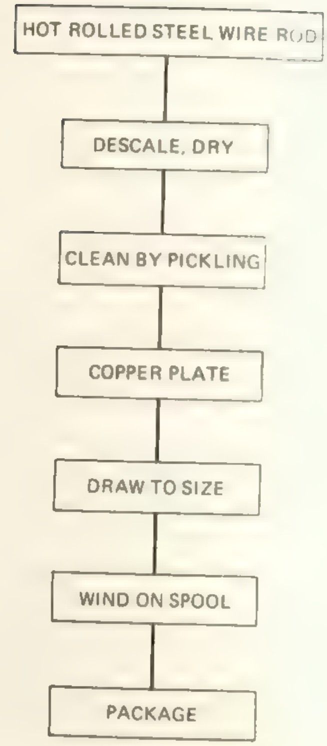
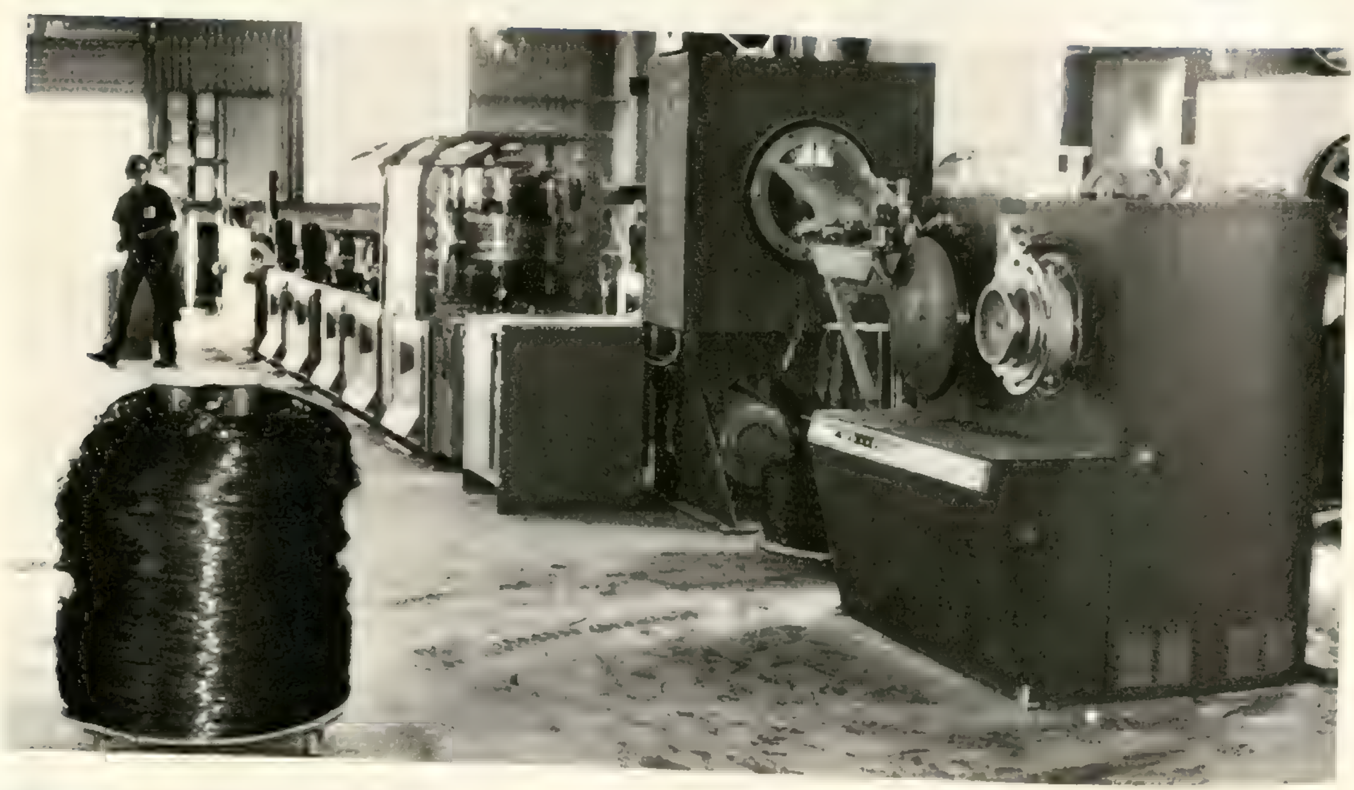


FIGURE 13-6 Flowchart for manufacturing solid electrode wire.

FIGURE 13-7 Wire drawing operation.



rous wires is essentially the same; however, different amounts of reduction per drawing die, different drawing lubricants, different heat treatments, and so on, are involved.

The solid steel electrode wires may not be "bare." Many suppliers provide a very thin copper coating on the wire. The copper coating is for several purposes. It improves the current pickup between contact tip and the electrode. It aids drawing and helps prevent rusting of the wire when it is exposed to the atmosphere.

Solid electrode wires are also made of various stainless steel analyses, aluminum alloys, nickel alloys, magnesium alloys, titanium alloys, copper alloys, and other metals. Specifications for these electrodes are shown in Figure 13-1.

When the wire is cut and straightened, it is called a welding rod, which is a form of filler metal used for welding or brazing which does not conduct the electrical current. If the wire is used in the electrical circuit, it is called a welding electrode and is defined as a component of the welding circuit through which current is conducted. The AWS designations are shown in Figure 13-8.

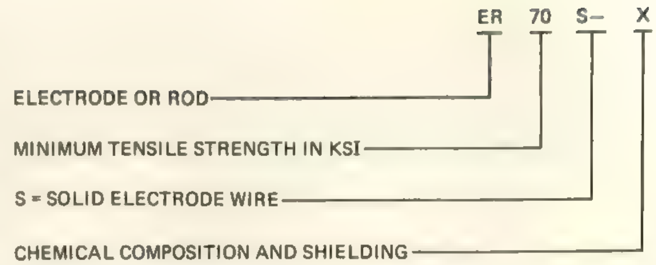


FIGURE 13-8 **AWS designations for solid electrode wire.**

The first two digits, ER, indicate that it is either an electrode or a welding rod. The next two digits stand for the minimum tensile strength in ksi. For carbon steel electrodes this number is 70. For low-alloy-steel electrodes the number can be 80 or higher. The next digit, which is the letter S, indicates a solid electrode wire or rod. If the letter C is used, it indicates a composite metal cored or stranded electrode rod. The last digit, X, follows a dash which indicates the chemical composition and shielding. These data are given in the specification.

Figure 13-9 is a summary of carbon steel electrodes for gas metal arc welding per AWS specification "Carbon Steel Filler Metals for Gas Shielded Arc Welding." The chemical composition and shielding gases used for low-alloy electrodes is more specific as given by the AWS specification "Low Alloy Steel Filler Metals for Gas Shielded Arc Welding."

The system for identifying solid bare carbon steel for submerged arc is as follows: The prefix letter E is used to indicate an electrode. This is followed by a letter which indicates the level of manganese (i.e., L for low, M for medium, and H for high manganese). This is followed

FIGURE 13-9 **Summary of carbon steel electrodes for GMAW** **(continued on page 422).**

IDENTIFICATION	WELDING CONDITIONS			TEST REQUIREMENTS (AS WELDED)			
AWS Classification	Current Electrode Polarity	External Gas Shield	Soundness Radio-graphic Test	All Tensile (min. psi)	Weld Yield (min. psi)	Metal El.% (min. 2 in.)	Impact Test Charpy V
E70S-2	DCEP	CO_2	Required	72,000	60,000	22	20 @ −20°F
E70S-3	DCEP	CO_2	Required	72,000	60,000	22	20 @ 0°F
E70S-4	DCEP	CO_2	Required	72,000	60,000	22	Not required
E70S-5	DCEP	CO_2	Required	72,000	60,000	22	Not required
E70S-6	DCEP	CO_2	Required	72,000	60,000	22	20 @ −20°F
E70S-7	DCEP	CO_2	Required	72,000	60,000	22	20 @ −20°F
E70S-G	Not specified	Not specified	Required	72,000	60,000	22	Not Required

Note: P—0.025 max.; S—0.035 max. Shielding gas may be argon-CO_2 or argon-O_2 mixture.

Identification	Chemical Composition					
AWS Classification	C	Mn	Si	Other		
E70S-2	0.6		0.40 to 0.70	Ti-0.05 to 0.15	Zi-0.02 to 0.12	Al-0.05 to 0.15
E70S-3	0.06 to 0.15	0.90 to 1.40	0.45 to 0.70			
E70S-4	0.07 to 0.15		0.65 to 0.85			
E70S-5	0.07 to 0.19		0.30 to 0.60	Al-0.50 to 0.90		
E70S-6	0.07 to 0.15	1.40 to 1.85	0.80 to 1.15			
E70S-7	0.07 to 0.15	1.50 to 2.00	0.50 to 0.80			
E70S-G	No chemical requirements					

Note: P—0.025 max.; S—0.035 max. Shielding gas may be argon-CO_2 or argon-O_2 mixture.

FIGURE 13-9 *(cont.)*

by a number which is the average amount of carbon in points or hundredths of a percent. The composition of some of these wires is almost identical with some of the wires in the gas metal arc welding specification.

The electrode wires used for submerged arc welding are given in AWS specification, "Bare Mild Steel Electrodes and Fluxes for Submerged Arc Welding." This specification provides both the wire composition and the weld deposit chemistry based on the flux used. The specification does give composition of the electrode wires (Figure 13-10).

When these electrodes are used with specific submerged arc fluxes and welded with prescribed procedures, the deposited weld metal will meet mechanical properties required by the specification.

In the case of the filler rods used for oxyfuel gas welding the prefix letter is R, but this is followed by a G, indicating that the rod is used expressly for gas weld-

FIGURE 13-10 Summary of mild steel electrode wire composition for SAW.

AWS Classification	Chemical Composition—Percent						
	C	Mn	Si	S	S	P	Total Other Elements
Low manganese classes							
EL8	0.10	0.30 to 0.55	0.05	0.035	0.03	0.30	0.50
EL8K	0.10	0.30 to 0.55	0.10 to 0.20	0.035	0.03	0.30	0.50
EL12	0.07 to 0.15	0.35 to 0.60	0.05	0.035	0.03	0.30	0.50
Medium manganese classes							
EM5K	0.06	0.90 to 1.40	0.40 to 0.70	0.035	0.03	0.30	0.50
EM12	0.07 to 0.15	0.85 to 1.25	0.05	0.035	0.03	0.30	0.50
EM12K	0.07 to 0.15	0.85 to 1.25	0.15 to 0.35	0.035	0.03	0.30	0.50
EM13K	0.07 to 0.19	0.90 to 1.40	0.45 to 0.70	0.035	0.03	0.30	0.50
EM15K	0.12 to 0.20	0.85 to 1.25	0.15 to 0.35	0.035	0.03	0.30	0.50
High manganese class							
EH14	0.10 to 0.18	1.75 to 2.25	0.05	0.035	0.03	0.30	0.50

ing. These letters are followed by two digits 45, 60, or 65, which designate the approximate tensile strength in 1000 psi.

In the case of nonferrous filler metals, the prefix E, R, or RB is used followed by the chemical symbol of the principal constituent metals in the wire. The initials for one or two elements will follow. If there is more than one alloy containing the same elements, a suffix letter or number may be added.

The American Welding Society's specifications are most widely used in the United States for specifying bare welding rod and electrode wires. There are also military specifications such as the MIL-E or -R types and federal specifications, normally the QQ-R type and AMS specifications. The particular specification involved should be used for specifying filler metals.

The most important aspect of solid electrode wires and rods is their composition which is given by the specification. The chemistry referred to is the composition of the electrode or rod itself. The specifications provide the limits of composition for the different wires and mechanical property requirements. The specification should be referred to for exact information.

The bare electrode wires are identified in several different ways. When the wire is coiled on a spool, a label is placed on the spool identifying the size and type of the electrode. When it is in coils or in drums, the label is placed on the drum or on a liner on the inside diameter of the coil.

For straight lengths of welding rod, two systems are used. For large-diameter nonferrous rods the classification number may be stamped in the metal. When the diameter is too small, small tags are stuck to each individual rod. These will show the classification number of the piece. An example of this is shown in Figure 13-11. Color coding has been used but is being supplanted by tags showing type numbers. In all cases the container holding the rods carries an identification label.

In the case of coiled electrode wire a maximum and minimum of cast and helix are specified. Normally, the cast is greater than the diameter of the package coil. This helps the electrode wire feed through cables and guns. The arc will tend to wander as the wire comes out of the welding gun tip if helix is too great.

Occasionally, on copper-plated wires, the copper may flake off in the feed roll mechanism and create problems. It may plug liners, and contact tips. Therefore, a light copper coating is desirable. The electrode wire surface should be reasonably free of dirt and drawing compounds. This can be checked by using a white cleaning tissue and pulling a length of wire through it. Too much dirt will clog the liners, will reduce current pickup in the tip, and may create erratic welding operation.

Temper or strength of the wire can be checked in a testing machine. Wire of a higher strength will feed better through guns and cables. The minimum tensile strength recommended by the specification is 140,000 psi (98 kg/mm^2).

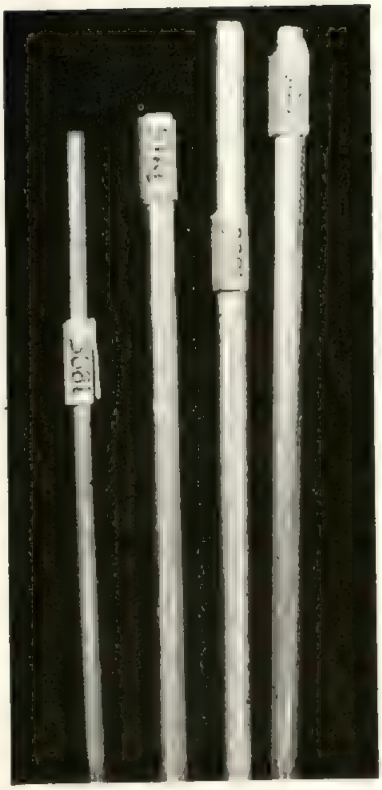


FIGURE 13-11 Identification of welding rods—tags.

Feedability is a measure of the ease with which the wire can be fed through a gun and cable assembly. It depends on all the factors just mentioned.

13-4 CORED ELECTRODE WIRES

The outstanding performance of the flux-cored arc welding process is made possible by the design of the cored electrode. This inside–outside electrode consists of a metal sheath surrounding a core of fluxing and alloying compounds. The compounds contained in the electrode perform essentially the same functions as the coating on a covered electrode (i.e., deoxidizers, slag formers, arc stabilizers, alloying elements, and may provide shielding gas).

There are three reasons why cored wires are developed to supplement solid electrode wires of the same or similar analysis.

1. There is an economic advantage. Solid wires are drawn from steel billets of the specified analyses. These billets are not readily available and are expensive. Also, a single billet might provide more solid electrode wire than needed.

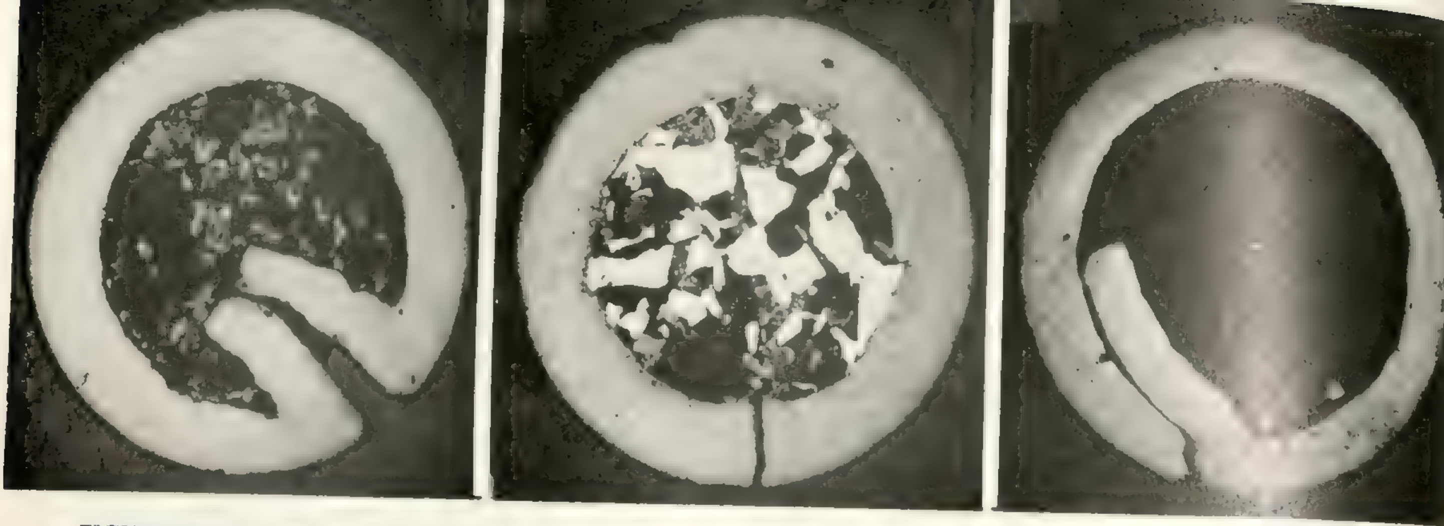


FIGURE 13-12 Cross section of various types of flux-cored electrodes.

2. Tubular wire production method provides versatility of composition and is not limited to the analysis of available steel billets.
3. Tubular electrode wires are easier for the welder to use than solid wires of the same deposit analysis, especially for welding pipe in the fixed position.

Figure 13-12 shows cross-sectional views of flux-cored electrodes. The tubular type is the most popular. The sheath or steel portion of the flux-cored wire comprises 75 to 90% of the weight of the electrode, and the core material represents 10 to 25% of the weight of the electrode. For a covered electrode, the steel represents 75% of the weight and the flux 25%. This is shown in more detail in Figure 13-13.

It is evident that more flux is used on covered electrodes than in a flux-cored wire to do the same job. This is because the covered electrode coating contains binders to keep the coating intact and also contains agents to allow the coating to be extruded.

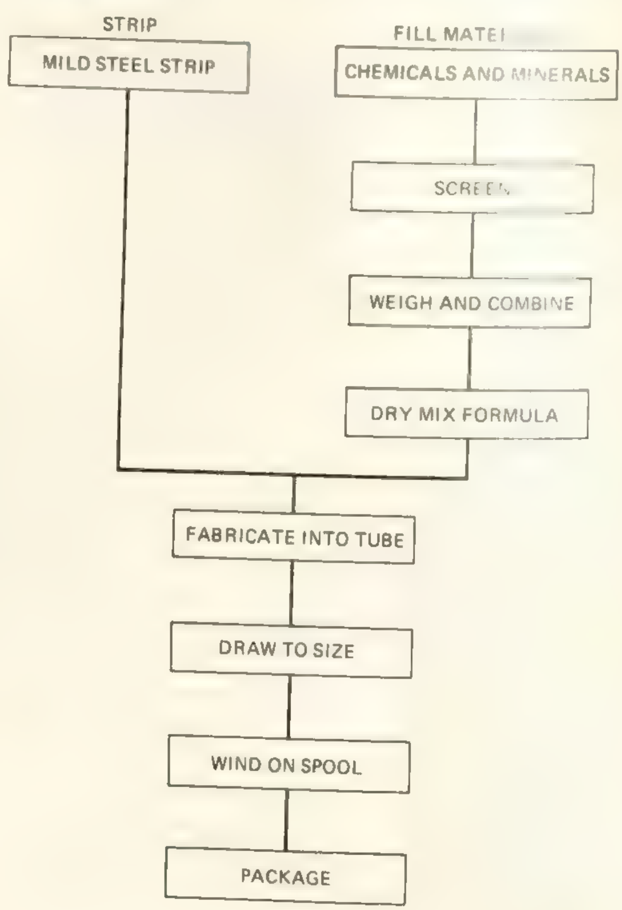
The manufacture of the flux-cored electrode is an extremely technical and precise operation requiring specially designed machinery. Figure 13-14 shows the simplified flowchart of the manufacturing operation.

Figure 13-15 shows a simplified version of the apparatus for producing tubular cored electrodes. Thin, narrow, flat, low-carbon steel strip passes through forming rolls which makes it into a U-shaped section. This U-shaped steel passed through a special filling device where a measured amount of the formulated granular core material is added. The flux-filled U-shaped strip then passes through closing rolls which form it into a tube and tightly compress the core materials. This tube is then

FIGURE 13-13 Summary of flux-to-steel ratios.

		Flux-Cored Electrode Wire (E70T-1)	Covered Electrode (E7016)
By area:	Flux	25%	55%
	Steel	75%	45%
By weight:	Flux	15%	24%
	Steel	85%	76%

FIGURE 13-14 Flowchart for manufacturing tubular electrode wire.



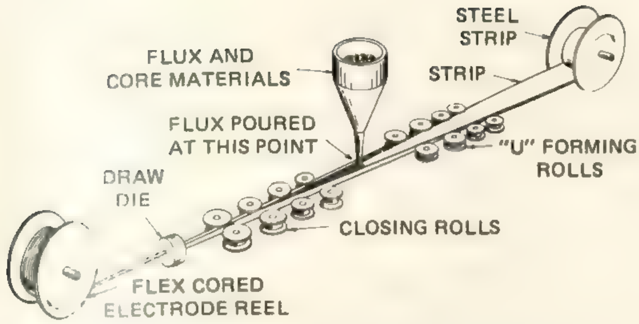
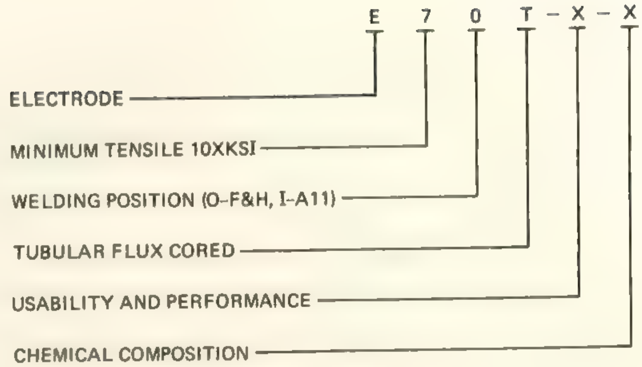


FIGURE 13-15 **Simplified manufacturing operation to make tubular wire.**



NOTE: LAST X ONLY FOR LOW ALLOY STEEL

FIGURE 13-16 **AWS designation for tubular electrode wire.**

pulled through drawing dies which reduce its diameter and further compress the core materials. Drawing tightly seals the sheath and secures the core materials inside the tube, thus avoiding discontinuities of the flux. The electrode may or may not be baked during, or between, drawing operations. This depends on the type of electrode and the type of materials enclosed in the sheath.

The drawing operations produce the various sizes of electrodes. The normal diameters are $\frac{1}{8}$-in. (3.2-mm), $\frac{7}{64}$-in. (2.8-mm) diameter, $\frac{3}{32}$-in. (2.4-mm), $\frac{5}{64}$-in. (2.0-mm) diameter, $\frac{1}{16}$-in. (1.6-mm) diameter, 0.045-in. (1.1-mm) diameter, and now 0.035-in. (0.9-mm) diameter. The $\frac{3}{32}$-in. (2.4-mm) diameter is the most popular. The finished cored electrode is packaged as a continuous coil, on spools, or in round drums.

Carbon steel and low-alloy steel flux-cored electrodes are classified by the American Welding Society. Two specifications are involved, "Carbon Steel Electrodes for Flux Cored Arc Welding" and "Low Alloy Steel Specifications for Flux and Cored Arc Welding." These must be consulted to determine the exact characteristic of each electrode type and the chemistry of the deposit weld metal. A table in the flux-cored welding process section gives a summary of these electrodes, welding polarity, whether external gas shielding is or is not required, test requirements, and minimum mechanical properties.

The system for identifying flux-cored electrodes is shown in Figure 13-16. The E indicates an electrode. The next digit stands for the minimum tensile strength as welded times 10 ksi. The next digit stands for welding position; O indicates flat or horizontal welding and 1 indicates all position welding. The next digit, a T, indicates a tubular or flux-cored electrode. The next digit following a dash (for carbon steel electrodes) indicates the usability and performance capabilities of the electrode wire. For low-alloy steel electrodes there are three numbers following the letter E, with the first two indicating the minimum tensile strength times 10 ksi. The digit following the letter T is changed and the dash follows the digit. The last digit indicates the chemical composition of the weld metal deposited.

The chemical composition required for the carbon steel and low-alloy steel electrodes is shown by the specifications. Following is a summary of electrode classifications.

E60T-7 Electrode Classification Electrodes of this classification are used without externally applied gas shielding and may be used for single- and multiple-pass applications in the flat and horizontal positions. Due to low penetration and to other properties, the weld deposits have a low sensitivity to cracking.

E60T-8 Electrode Classification Electrodes of this classification are used without externally applied gas shielding and may be used for single- and multiple-pass applications in the flat and horizontal positions. Due to low penetration and to other properties, the weld deposits have a low sensitivity to cracking.

E70T-1 Electrode Classification Electrodes of this classification are designed to be used with CO_2 shielding gas for single- and multiple-pass welding in the flat position and for horizontal fillets. A quiet arc, high deposition rate, low spatter loss, flat-to-slightly convex bead configuration, and easily controlled and removed slag are characteristics of this class.

E70T-2 Electrode Classification Electrodes of this classification are used with CO_2 shielding gas and are designed primarily for single-pass welding in the flat position and for horizontal fillets. However, multiple-pass welds can be made when the weld beads are heavy and an appreciable amount of admixture of the base and filler metals occurs.

E70T-3 Electrode Classification Electrodes of this classification are used without externally applied gas shielding and are intended primarily for depositing single-pass, high-speed welds in the flat and horizontal positions on light plate and gauge thickness base metals. They should not be used on heavy sections or for multiple-pass applications.

E70T-4 Electrode Classification Electrodes of this classification are used without externally applied gas shielding and may be used for single- and multiple-pass applications in the flat and horizontal positions. Due to low penetration and to other properties, the weld deposits have a low sensitivity to cracking.

E70T-5 Electrode Classification This classification covers electrodes designed primarily for flat fillet or groove welds with or without externally applied shielding gas. Welds made using CO_2 shielding gas have better quality than those made with no shielding gas. These electrodes have a globular transfer, low penetration, slightly convex bead configuration, and a thin, easily removed slag.

E70T-6 Electrode Classification Electrodes of this classification are similar to those of the E70T-5 classification, but are designed for use without an externally applied shielding gas.

E70T-G Electrode Classification This classification includes those composite electrodes that are not included in the preceding classes. They may be used with or without gas shielding and may be used for multiple-pass work or may be limited to single-pass applications.

The E70T-G electrodes are not required to meet chemical, radiographic, bend test, or impact requirements; however, they are required to meet tension test requirements. Welding current type is not specified.

The flux-cored electrode wires are considered to be *low hydrogen*, since the materials used in the core do not contain hydrogen. However, certain of these materials are hygroscopic and thus tend to absorb moisture when exposed to a high-humidity atmosphere. Electrode wires are therefore packaged in special containers to prevent this. It is recommended that these electrode wires be stored in a dry room.

Stainless Steel Tubular Wires

Flux-cored tubular electrode wires are available which deposit stainless steel weld metal corresponding to the AISI compositions. These electrodes are covered by the AWS specification, "Flux-Cored Corrosion Resisting Chromium and Chromium-Nickel Steel Electrodes." These electrodes are identified by the prefix E followed by the standard AISI code number. This is followed by the letter T indicating a tubular electrode. Following this and a dash are four possible suffixes as follows:

- -1 Indicates the use of CO_2 gas for shielding and DCEP.
- -2 Indicates the use of argon plus 2% oxygen for shielding and DCEP.
- -3 Indicates no external gas shielding and DCEP.
- -G Indicates that gas shielding and polarity are not specified.

Tubular or flux-cored electrode wires are also used for surfacing and submerged arc welding applications.

13-5 PACKAGING OF SOLID AND CORED ELECTRODE WIRES

Filler materials are packaged in a variety of forms to meet the user's welding equipment, storage, and handling requirements. The American Welding Society has established standards for some spool and coil sizes, but there is no national standard for packaging of electrode wires. The industry has established various forms of packages which are described. There are exceptions and additions to this compilation, but in general, filler wires can be obtained in the following basic packages: spools, small coils, reels, drums, or payoff packs and large coils.

Spools

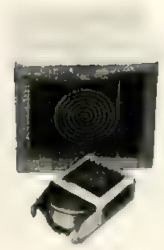
Spools made of plastic or composition wood are available in a variety of sizes and carry from 1 to 60 lb of electrode wire, depending on spool size and type of wire. In general, spools are wrapped in a thick plastic bag to provide maximum protection from moisture. Nonferrous wires are normally wrapped with protective paper. Standard 4-in. spool dimensions are shown in Figure 13-17. The 1- and 2-lb spools are usually level wound, individually boxed, and normally are used for nonferrous wires. The small spools are used on hand guns or for orbital heads doing gas tungsten arc welding.

The 10-lb spools are wound transversely on 8-in. spools (Figure 13-18) and normally individually wrapped. They are usually used for carbon steel or stainless steel electrode wires. Also, they are often used with portable wire feeders.

The 15-lb spools are slightly larger, carry the same type of wire, but are used for different type of equipment, usually portable wire feeders.

The 25- and 30-lb spools are transversely wound on the 12-in. spools (Figure 13-19) and normally wrapped in plastic bags. This is the most popular package. The same size spool is used for aluminum electrode wire, which is approximately 15 lb of wire per spool.

The 50- and 60-lb spools are transversely wound on 14-in. spools and individually wrapped. These are normally used for carbon steel, stainless steel, and flux-cored electrode wires. This is used on standard wire feeders. Spools are nonreturnable. Spools should have one continuous length of electrode wire made from a single lot of material.



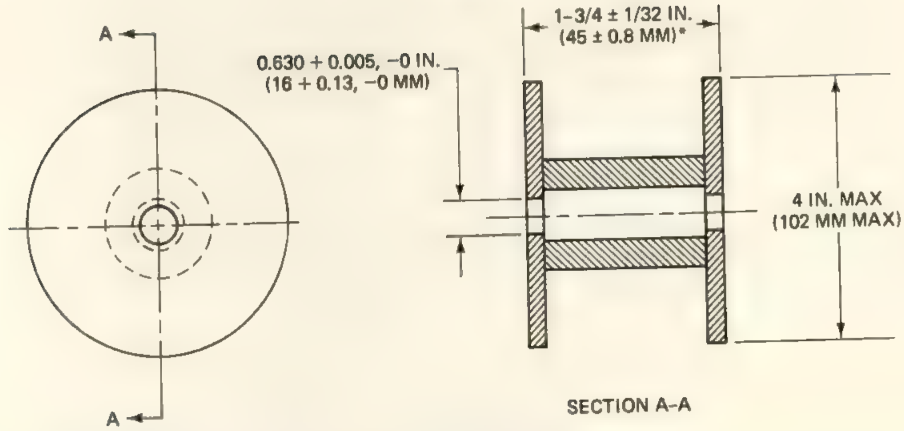
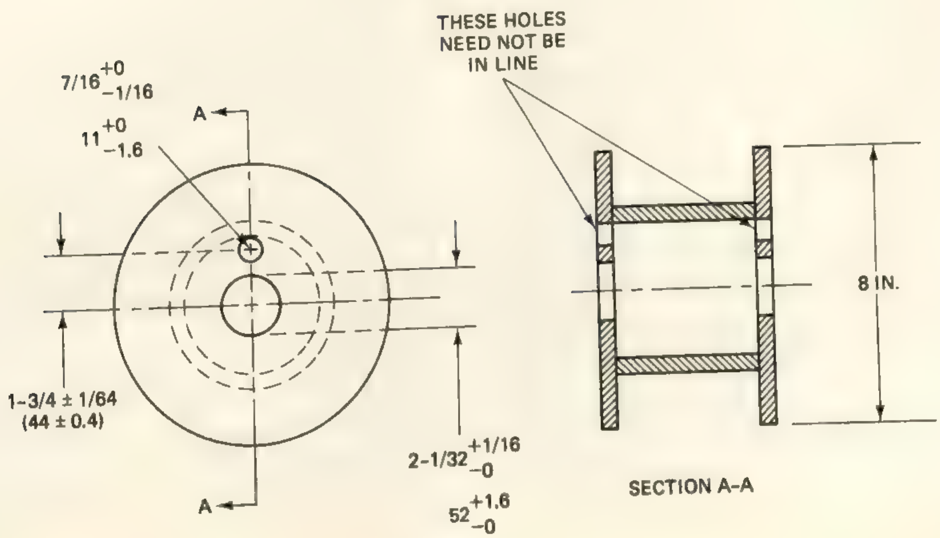


FIGURE 13-17 Four-inch standard spool and dimensions.

FIGURE 13-18 Eight-inch standard spool and dimensions.



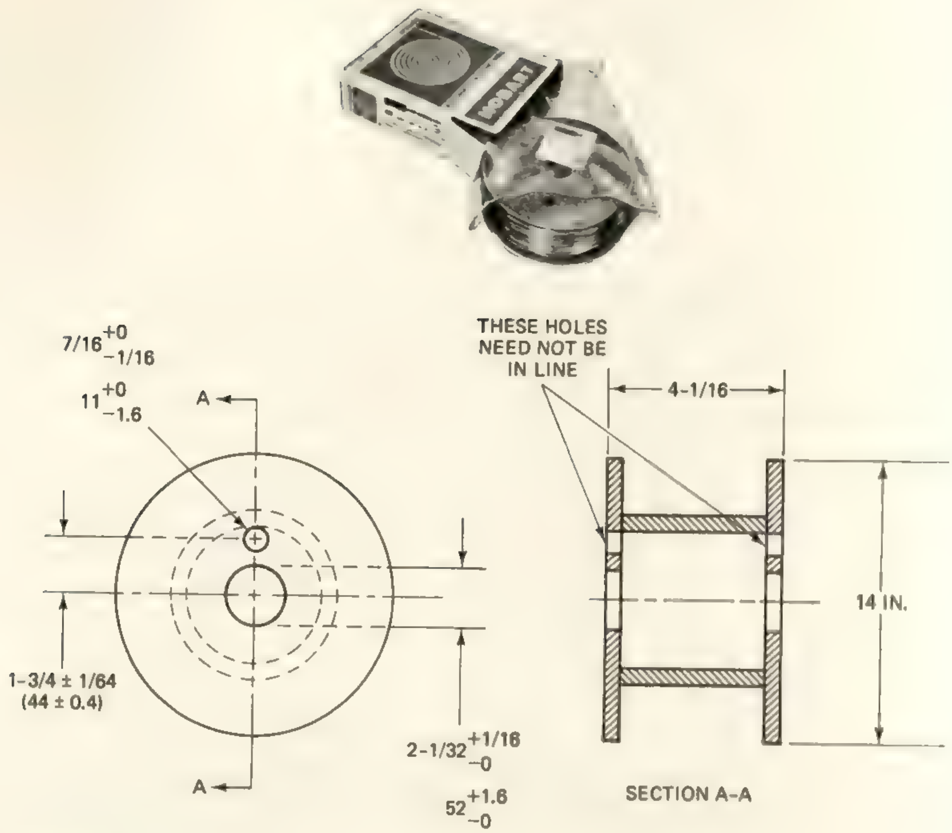


FIGURE 13-19 **Fourteen-inch standard spool and dimensions.**

Small Coils

Coils are supplied with a cardboard inner liner to avoid the expense of spools. They require a special spider to hold them on the dispensing equipment. The smaller coils come in 50- or 60-lb sizes. They are transversely wound, the ID of the core is 12 in., and they are 4 in. wide. Each coil is individually wrapped in plastic bags and normally packed in a corrugated carton. The small coils are used for carbon steel, solid electrode wires, and for flux-cored electrode wires. The coil and coil dimensions are shown in Figure 13-20. The weight of electrode wire in coils should not vary by more than 10%.

Reels

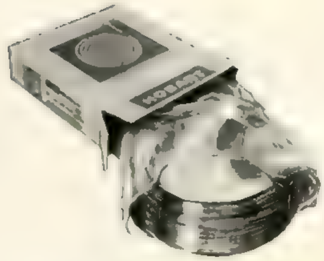
Reels are designed for larger packages of carbon steel solid electrode wire and flux-cored electrode wires. They require special equipment for dispensing the electrode wire. Motorized dispensers are sometimes used to reduce the load on the wire feed motor (Figure 13-21). Reels of solid electrode wire are supplied in 250-, 750-, and 1000-lb sizes. Reels of cored electrode wire are supplied in 250-, 600-, and 800-lb sizes. Reels are transversely wound and individually wrapped in a protective paper barrier. They are normally palletized and protected with a polystyrene shrink film covering to provide protection during shipment and storage. Reels are made of wood and are nonreturnable.

Drums/Payoff Packs

Another method of providing large quantities of electrode wire is by the use of drums or payoff packs. The drums shown in Figure 13-22 are made of heavy cardboard construction and will contain 250, 500, or 700 lb of electrode wire. These are normally used for solid carbon steel wire or flux-cored electrode wires. Wire is placed in the drums to ensure a snarl-free payoff of the electrode with the drum usually rotating. Drums are palletized and covered with the polystyrene shrink film to provide protection during shipment and storage. Drums are nonreturnable.

Large Coils

Electrode wires are also provided in large coils, usually 1000 lb, normally used for automatic welding operations (Figure 13-23). Normally, coils are strapped to a pallet



COIL WITH SUPPORT, STANDARD DIMENSIONS AND WEIGHTS

Standard Size	Net Weight of Filler Metal		Dimensions			
			Inside Diameter of Liner		Width of Wound Filler Metal, Max.	
in. (mm)	lb	kg	in.	mm	in.	mm
All	25	11	12 ± 1/8	305 ± 3	2-1/2	65
1/16 (1.6) and larger	50 and 60	23 and 27	12 ± 1/8	305 ± 3	4-5/8	120
0.054 (1.4) and smaller	50 and 60	23 and 27	12 ± 1/8	305 ± 3	b	b

FIGURE 13-20 Standard dimensions of small coils.

Type of Package	Package Size		Net Weight of Filler Metal	
	in.	mm	lb	kg
Reels	22 OD	560 OD	250	110
	30 OD	760 OD	750	340

FIGURE 13-21 Standard sizes of reels.

FIGURE 13-22 Standard sizes of drums.

Type of Package	Package Size		Net Weight of Filler Metal	
	in.	mm	lb	kg
Drums	15–1/2 OD	400 OD	As specified by purchaser	
	20 OD	500 OD		
	23 OD	600 OD		

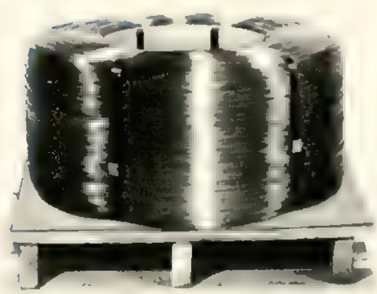


FIGURE 13-23 1000-pound coil.

and are covered with polystyrene shrink film to provide protection during shipment and storage. Large coils require special dispensing equipment.

Selection of Package

Figure 13-24 is a summary of the different types of packaging of electrode wires. It shows the normal dimensions for such packages and the type of wire usually employed. This is not the total packaging method since some suppliers will provide special sizes of spools, coils, reels, and so on, for specialized equipment. Consult your supplier for the exact size of packages supplied.

In general, electrode wire is less expensive when ordered in larger packages. Additionally, the supply of electrode wire does not need to be changed as often. This is important when multiple welding heads are a part of the same system. This avoids frequent downtime to renew

Weight (lb)	Flange Diameter[a] (in.)	Hub Diameter (in.)	Width (in.)	Inside Diameter (in.)	Arbor Hole (in.)	Engaging Hole (in.)	Engaging Hole in Both Flanges Off Center (in.)
Spools							
1	4	1½	1¾	Varies	⅝	—	—
2	4	2 9/16	1¾	Varies	⅝	—	—
10	8	3¾	2⅛	Varies	2 1/16	—	—
15	8	3⅞	3	Varies	2 1/16	—	—
10–15	12	8¼	4	Varies	2 1/16	7/16	1¾
30	12	8¼	4	Varies	2 1/16	7/16	1¾
25	12	8¼	4	Varies	2 1/16	7/16	1¾
50	14	8¼	4	Varies	2 1/16	7/16	1¾
60	14	8¼	4	Varies	2 1/16	7/16	1¾
Coils (small)							
50	NA	NA	4	12	NA	NA	NA
60	NA	NA	4	12	NA	NA	NA
Reels (large spools)							
250	22	16½	11	Varies	1 5/16	⅞	2½
600	30	16½	11	Varies	1 5/16	⅞	2½
750	30	16½	11	Varies	1 5/16	⅞	2½
800	30	11¾	11½	Varies	Varies	Varies	Varies
1000	30	11¾	11½	Varies	Varies	Varies	Varies
Drums	Outside Dia.						
250	15½	NA	NA	20	NA	(16 in. hght., 13 in. core)	
500	20	NA	NA	20	NA	(20 in. hght., 13 in. core)	
600	20	NA	NA	23	NA	(31 in. hght., 16 core)	
750	23	NA	NA	23	NA	(34 in. hght., 13 core)	
Coils (large)							
1000	NA	NA	Varies	Varies	NA	NA	NA

[a]NA, not applicable.

FIGURE 13-24 **Summary of packages for welding electrode wire.**

the electrode supply. However, larger packages require special dispensing equipment. These are different for the different packages. See the section on electrode wire dispensing system for details. The wire supplier will normally be able to provide the types of dispensing equipment required for the package supplied.

Cast and Helix of Wire

AWS specifications require that cast and helix of wire on spools or coils must be suitable for feeding in an uninterrupted manner using automatic and semi automatic welding equipment. The cast of a spooled electrode wire or filler metal wire wound on a spool is measured by removing a loop or ring of wire from the spool. When cut from the spool and laid on a flat surface, it should form an unrestrained circle of not less than a minimum diameter nor greater than a maximum diameter (Figure 13-25).

The helix of coiled wire is measured with the loop or ring mentioned above. The loop or ring is placed on a flat surface without restraint. The maximum distance of any portion of the loop above the flat surface must not be greater than the dimension shown for the helix in the same figure. The filler metal received from most manufacturers will meet these requirements.

FIGURE 13-25 Cast and helix requirements for electrode wires.

AWS Classification	Type of Package	Standard Size in. (mm)	Cast in.	Cast mm	Maximum Helix in.	Maximum Helix mm
All	4-in. (100-mm) spools	0.045 (1.2) and less	4–9	100–230	½	13
All	All except 4-in. (100-mm) spools	0.030 (0.8) and less	12 min.	305 min.	1	25
		0.035 (0.9) and larger	15 min.	380 min.	1	25

13-6 WELDING FLUXES

There are a number of different types of fluxes used in welding, brazing, and soldering. These include fluxes for oxy fuel gas welding, fluxes for brazing, fluxes for soldering, fluxes for oxygen cutting of certain hard-to-eut metals, fluxes for electroslag welding, and fluxes for submerged arc welding. The American Welding Society provides a specification for weld metal deposited by different combinations of steel electrodes and proprietory fluxes for submerged arc welding. The American Welding Society provides a brazing flux type number and an indication of the ingredients of the flux. It has also recommended useful temperatures and the forms of the flux. There are various government specifications covering brazing fluxes. The manufacturers of brazing flux provide instructions for the application and use of their fluxes.

Fluxes for gas welding are covered by various government specifications. Manufacturers' recommendations should be followed.

Submerged Arc Flux

The function of the submerged arc flux is to produce a slag that will protect the molten metal from the atmosphere by providing a mechanical barrier. When it is molten, this slag should provide ionization to permit a stable arc. It should be fluid and of relatively low density so that it will float and cover the top of the deposited weld metal. The melting temperature should be related to that of the molten weld metal and it should have a different coefficient of expansion so that it can easily be removed after cooling. The slag should provide deoxidizers to help cleanse and purify the weld metal. It should also help reduce phosphorus and sulfur that might be present in the base metal. It should not introduce hydrogen into the weld. Finally, the flux should be granular and convenient to handle, should not provide noxious fumes, but should provide for a smooth weld surface.

Submerged arc fluxes consist of mixtures of chemicals and minerals in various combinations to provide the properties just mentioned. Every grain of submerged arc flux should be similar in composition to the others and uniform in size. In the use of submerged arc flux, the granular material is placed over the welding joint and the heat of the arc causes it to melt and produce a molten slag. All of the flux placed over the weld does not melt and the unmelted flux can be removed and reused. Upon cooling, the flux that melts transforms to a glass-like slag which must be removed from the weld deposit. The melted slag should not be used for welding since the deoxidizers, and other cleansing elements in the flux, are expended during melting.

There are three types of submerged arc welding fluxes based on the method of manufacturing.[2] The three types are (1) fused flux, (2) agglomerated flux, and (3) bonded flux.

The ingredients for the flux must be ground, sized, and mixed prior to heating. In the case of *fused fluxes*, the mixture is melted in an electric or gas-fired furnace. The mixture is melted in a temperature range of 2912 °F (1600 °C). After melting, the molten flux is poured into water or onto a chilled plate to produce a glassy material. This material is then dried, crushed, and sized, by means of screens, packaged; it is then ready for use.

The second method of manufacturing fluxes is the *agglomerated* method. Materials are dry mixed in the same way, except that a binder such as sodium or potassium silicate is added, after which the material is wet mixed. The mixture is then fed into a rotary kiln operating at approximately 1832 °F (1000 °C). Inside the kiln, by means of a tumbling process, the mixture forms into small balls and the ingredients tend to grow together and become larger. When they are properly heated these balls become very tough. After cooling, the balls are ground in the same manner as mentioned above, sized, packaged, and ready for use.

The third method of making fluxes is the *bonded* method, and this is very similar to the agglomerated method, except that the mixture is bonded at a lower temperature. After the pellets are bonded, hardened, and cooled they are ground, sized, packaged, and ready for use. Figure 13-26 is a simplified flowchart that applies to either agglomerated or bonded fluxes.

Each manufacturing method produces fluxes that are suitable for submerged arc welding and each has certain advantages and disadvantages. In the case of the fused flux, the high temperatures involved require considerable more energy for production. In addition, many of the elements used for deoxidation are partially expended at the high heat temperature and thus must be enriched to provide sufficient deoxidizing power for welding. The advantage is that all the grains of the flux are of uniform composition and in general the resulting flux is nonhygroscopic; that is, it will not pick up moisture.

In the case of the bonded and agglomerated fluxes the temperatures are lower and therefore less energy is consumed. Additionally, the deoxidizers are not dissipated and are therefore active during the welding operation.

The composition of the welding fluxes can be varied to provide ranges in the melting and solidification temperatures, the viscosity, the current-carrying capacity, the arc stability, welding speed capacity, shape and appearance of the weld, and the ease of the slag removal. The slag metal reaction during the welding operation is extremely complex and beyond the scope of this book. For additional information consult Ref. 1.

Submerged arc flux can be described as neutral, acidic, or basic while it is in the molten stage. If absolute neutrality cannot be obtained it is best then for the flux

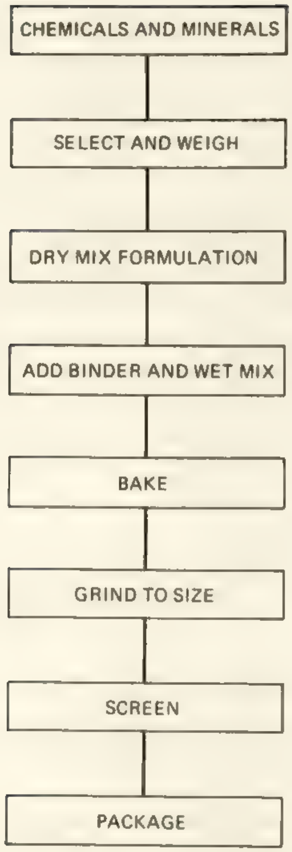


FIGURE 13-26 Flowchart for manufacturing submerged arc flux.

to be basic, so that it will reduce impurities in the weld metal. The most ideal flux will be metallurgically inactive, which means that the composition of the deposited weld metal will be the same as the composition of the welding electrode. This is not possible over the entire range of welding electrode compositions available and thus a loss or buildup of certain elements may occur. The flux can be used to increase the amount of alloy added to the deposit. Alloying elements can be added via the electrode or the flux. In general, it is more economical to add alloying elements through the flux. This is particularly important when doing surfacing or when welding on alloy base metals.

Sizing is established by means of controlled mesh screens set to both the upper and lower limits of the size allowed for each particle. For example, a 12-mesh screen allows all particle sizes smaller than a certain size to fall through the screen. At the other end would be a 200-mesh screen, which would keep all the particles except the very fine particles from falling through. The resulting flux would have a maximum size allowed through a 12-mesh, a minimum size greater than that allowed to fall through the 200-mesh screen. If there are too many fines in the flux it will tend to reduce the freezing period of the flux and it cannot be used for high-speed or circumferential welding. Larger sizes provide for higher-speed welding but allow arc flash through the layer of flux. Manufacturers provide fluxes between two limits since these sizes are recommended for most welding applications.

Submerged arc fluxes are classified according to the mechanical properties of the weld metal made with the specific electrode wires. This information is provided in the section on submerged arc welding. It is based on the AWS specification shown for submerged arc welding early in this chapter. The specific AWS specifications should be consulted since they are revised periodically.

Electroslag Fluxes

Electroslag fluxes are similar to submerged arc fluxes except that they are normally the fused type. Electroslag flux performs differently during the welding operation than submerged arc fluxes. The electrical conductivity of the flux makes the electroslag welding process operate. The flux becomes molten in a pool and the electrode wire melts in the heated bath. It is the resistance of the bath to the welding current flowing between the electrode and the work which maintains the bath at the high temperature. The flux is designed to provide a balance between conductivity and bath temperature for proper electroslag welding. In addition, the flux provides elements to purify and deoxidize the weld metal and also prohibits the oxygen and nitrogen of the air from coming in contact with the molten weld metal. The electroslag flux must have a lower density than steel so that it floats above the molten metal.

The criteria for selecting electroslag fluxes are based on the combination of flux and electrode wire. Tests must be made with standardized electrode wires and proprietory fluxes[3] to qualify procedures.

13-7 OTHER WELDING MATERIALS

There are other filler metals and special items normally consumed in making welds. These include the nonconsumable electrodes—tungsten, carbon, and other materials, including backing tapes, backing devices, and flux additives. Another type of material consumed in making a weld are the consumable rings used for root-pass welding of pipe. Additionally, there are ferrules used for stud welding and the guide tubes in the consumable guide electroslag welding method. Other filler materials are solders and brazing alloys.

Nonconsumable Electrodes

There are two types of *nonconsumable electrodes.* The carbon electrode is a nonfiller metal electrode used in arc welding or cutting, consisting of a carbon graphite rod which may or may not be coated with copper or other

coatings. The second is the tungsten electrode, defined as a nonfiller metal electrode used in arc welding or cutting made principally of tungsten. The American Welding Society does not provide specification for carbon electrodes but there is a military specification, MIL-E-17777C, entitled, "Electrodes Cutting and Welding Carbon-Graphite Uncoated and Copper Coated." This specification provides a classification system based on three grades: plain, uncoated, and copper coated, also copper coated with lock joint ends. It provides diameter information, length information, and requirements for size tolerances, quality assurance, sampling, various tests, and so on. Most manufacturers of carbon electrodes provide information indicating the type and size to be used for a specific application. Applications include carbon arc welding, twin carbon arc welding, carbon cutting, and air carbon arc cutting and gouging.

The American Welding Society provides a specification for tungsten electrodes entitled, "Tungsten Arc Welding Electrodes." These electrodes are used for gas tungsten arc welding, plasma arc welding, and atomic hydrogen arc welding. This specification provides for four classes of electrodes in various size diameters and lengths and with two types of finish. The four classifications relate to the composition of the tungsten whether it is pure tungsten or tungsten with small amounts of thorium or zirconium added to improve electron emission. The information concerning tungsten electrodes was covered in Section 5-2.

Backing Materials

Backing materials are being used more frequently for welding. Special tapes exist, some of which include small amounts of flux, which can be used for backing the roots of joints. There are also different composite backing materials, for one-side welding. There are no specifications covering these materials, but more information about them will be provided in Section 26-3.

Consumable rings are used for making butt welds in pipe and tubing. These are rings made of metal that are tack welded in the root of the weld joint and are fused into the joint by the gas tungsten arc. There are four basic classes of rings called consumable insert rings. The AWS provides a specification[(4)]: Class 1 is called A-shaped or Inverted T, Class 2 is called J-shaped, Classes 3 and 5 are rectangular and sometimes called K-shaped, and Class 4 is called Y-shaped. The rings are available in different analyses to match the pipe metal and size.

Submerged Arc Flux Additives

Specially processed metal powder is sometimes added to the flux used for the submerged arc welding process. Additives are provided to increase productivity or enrich the alloy composition of the deposited weld metal. In both cases, the additives are of a proprietary nature and are described by their manufacturers indicating the benefit derived by using the particular additive. Since there are no specifications covering these types of materials, the manufacturer's information must be used.

Electroslag Guide Tubes

There are two types of guide tubes in common use for the consumable guide method of electroslag welding. Guide tubes may be bare or covered. When they are covered they are covered with a coating material that has a composition similar to the composition of the electroslag flux. Both types of tubes are consumed while the weld is being made, and the metal part of the tube becomes a portion of the deposited weld metal. The guide tube is a relatively small percentage of the deposit. The covered guide tube utilizes the flux covering to augment the flux used in the electroslag welding process. There are no AWS specifications for guide tubes; however, they are normally seamless steel tubes of a low-carbon composition. The AISI C1010 composition is often used. Guide tubes are specified by the inside and outside diameter. The flux covering is proprietary and is compatible with the same manufacturer's electroslag flux.

Ceramic Ferrules

Ceramic ferrules are used in the stud welding process. These are small, specially designed short hollow cylinders that fit over the end of the stud and protect the molten metal from the atmosphere during welding. The ferrules also help mold the molten weld metal to an acceptable weld contour. Ceramic ferrules are available for all different sizes of round studs and for many square or rectangular types. They are available from the stud manufacturer and are made to fit the stud sizes available. A ferrule is used only once and is easily broken away from the weld since it is very brittle. All manufacturers of studs provide the ceramic ferrules. No specifications exist for these items.

Solders

There are many different solder compositions and they are considered filler materials. Specifications for solder are issued by the American Society of Testing and Materials. The information about the different solders was summarized in Section 7-3.

Brazing Alloys

The brazing alloys are covered by a specification issued by the American Welding Society shown previously. The information about the different brazing alloys was summarized in Section 7-2.

Strip Electrodes

Strip electrodes are used for overlaying, usually stainless steels. They come in different thicknesses and widths. There are no specifications covering the size. The analysis is covered by the steel specifications.

QUESTIONS

13-1. What are the four basic filler metals?

13-2. What is the difference between AWS and ASME specifications for welding filler metals?

13-3. Who tests and certifies welding filler metals?

13-4. List the major functions of a coating on a covered electrode.

13-5. What is a low-hydrogen coating?

13-6. How are electrodes reconditioned after they become damp?

13-7. Explain "fingernailing" and the reasons for it.

13-8. How are bare solid steel electrodes specified? Give an example.

13-9. What is the purpose of a thin copper coating on a "bare" electrode wire?

13-10. In GMAW can argon-oxygen shielding gas be substituted for CO_2 shielding gas for welding carbon steel?

13-11. How are cut lengths of stainless steel rods identified?

13-12. What different packages are available for solid, bare electrode wires?

13-13. How are "cast" and "helix" measured? How do they affect welding?

13-14. What is the function of the core of a flux-cored electrode?

13-15. Explain the specification system for flux-cored steel electrodes.

13-16. Why is electrode wire less expensive when purchased in larger packages?

13-17. What welding processes normally use flux?

13-18. How is submerged arc flux made? Name two types.

13-19. What organization issues specifications for solder?

13-20. Explain the AWS classification system for tungsten electrodes.

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1. "Filler Metals Comparison Chart," AWS-FMC, American Welding Society, Miami, Fla.
2. C. E. Jackson, "Fluxes and Slags in Welding," Bulletin 190, Welding Research Council, New York, December 1973.
3. Howard B. Cary, "Porta-slag Welding," EW-412, Hobart Brothers Company, Troy, Ohio.
4. "Specifications for Consumable Inserts," AWS A5.30, American Welding Society, Miami, Fla.

14

Gases Used in Welding

OUTLINE

14-1 SHIELDING GASES

The major purpose of the shielding gas is to protect the arc area from the atmosphere. The shielding gas displaces the air and does not allow the atmospheric gases—nitrogen, oxygen, small amounts of helium, CO_2, and water vapor, and so on—to come into contact with the molten metal or the electrode.

All the arc welding processes have some mechanism for shielding the arc area from the atmosphere. In shielded metal arc welding the disintegration of the coating creates gas which protects the molten metal from the atmosphere. In flux-cored arc welding the disintegration of the core material, which may be supplemented by shielding gas, provides shielding from the atmosphere. In carbon arc welding the slow disintegration of the carbon electrode creates CO_2 gas, which shields the molten metal, and in submerged arc welding the granular flux performs this function. For gas metal arc welding and gas tungsten arc welding the shielding gases must be supplied and directed around the arc area to provide protection from the atmosphere. The secondary purpose of the shielding gas is to establish the metal transfer mode and the deposited weld characteristics in gas metal arc welding.

The shielding efficiency relates to how well the shielding gases displace the atmosphere from the arc area. This depends on the design of the nozzle, the distance from the nozzle to the work, the internal diameter or size of the nozzle, the gas flow rate, side winds, and the purity of the shielding gases. This is discussed in more detail later.

Shielding gases are either inert or active. Inert gases will not combine chemically with other elements. There are only six inert gases: argon, helium, neon, crypton, xenon, and radon. All of these except argon and helium are too rare and expensive to be used for gas-shielded welding. Inert gases must be used with the gas tungsten arc welding process and are normally used for welding nonferrous metals with either gas tungsten or gas metal arc welding.

Active gases are either oxidizing or reducing. Active gases will combine with molten metal. Oxidizing gases are any shielding gas that contains oxygen. Reducing gases are any shielding gas that attracts oxygen. Following is a brief description of the different gases used for arc shielding. Pure gases and mixtures of two or three gases are employed. A better understanding of each gas will provide a basis for understanding the reasons for different gas mixtures. Properties of pure gases involved are shown in Figure 14-1.

Several properties of gases have an effect on welding. Most of the gases are nontoxic but are an asphyxiant, meaning that a concentration of this gas will create suffocation due to the absence of oxygen. Too much oxygen or too much nitrogen in the breathing atmosphere will cause damage to humans.

The specific gravity relates to the weight of the gas with respect to air. The specific gravity of air is 1. Lightweight gases such as helium will float away and will not be an efficient shield. Heavier gases will displace air in enclosed areas.

Thermal conductivity relates to the heat in the arc column and whether it will create a small or a larger arc column; also, how fast the heat will travel in the gas.

Ionization potential established the ease of arc initiation and arc stability. The lower the ionization potential, the easier it is to start the arc. The higher the ionization potential, the hotter the arc.

Gases are diatomic or monatomic. A diatomic gas demonstrates disassociation of the molecules in the arc. This process absorbs heat energy, followed by recombination away from the arc, which releases latent heat. Monatomic gases do not disassociate.

The most important item with respect to shielding gases is its purity. In all cases the purity must exceed 99%. This is governed by specifications which are shown for each gas.

Gas Shielding Efficiency

With gas-shielded arc welding processes, specifically gas tungsten arc, gas metal arc, and flux-cored arc welding with external gas shielding, the quality of the weld depends on the efficiency of the atmosphere protection provided by the shielding gas. Figure 14-2 shows the surface of a gas tungsten arc weld on aluminum with proper gas shielding and with an inefficient shield. Figure 14-3 shows a gas metal arc weld on carbon steel with an effi-

FIGURE 14-1 Properties of inert and active gases.

Property	Air	Argon	Carbon Dioxide	Helium	Nitrogen	Oxygen	Hydrogen
International symbol and cylinder marking	Air	Ar	CO_2	He	N_2	O_2	H_2
Type of gas	Mixture oxidizing	Inert	Active oxidizing	Inert	Not true inert gas	Active oxidizing	Active reducing
Structure		Monatonic	Diatonic	Monatonic	Diatonic	Diatonic	Diatonic
Molecular weight	28.98	39.94	44.01	4.003	28.016	32.00	2.016
Boiling point (at 1 atm) F°	−317.8	−302.6	−109[a]	−452.1	−320.5	−297.3	−422.9
C°	−194	−184	−178	−269	−196	−182	−252
Specific volume ($ft^2 lb$) @70°F, 1 atm	13.4	9.67	8.76	96.71	13.8	12.1	192.0
Density (lb/ft^3)@70°F and 1 atm	0.0749	0.1034	0.1125	0.0103	0.0725	0.0828	0.0052
Specific gravity (air = 1)	1.000	1.380	1.530	0.137	0.967	1.105	0.069
Thermal conductivity (Btu/hr)	0.0140	0.0093	0.0085	0.0823	0.0146	0.0142	0.096
Ionization potential (electron volts)	–	15.7	14.4	24.5	15.51	12.5	15.6
Maximum allowable concentration	100%	Nontoxic asphyxiant	Nontoxic 5,000 ppm	Nontoxic asphyxiant	Nontoxic 82%	25%	Nontoxic asphyxiant

[a]Sublimes directly from a solid to a gas at −109°F (−178°C) and a pressure of 1 atmosphere.
Note: The shipping containers of all these gases (except hydrogen) would be marked "Nonflammable Compressed Gas." The shipping containers of hydrogen would be marked "Flammable Compressed Gas."

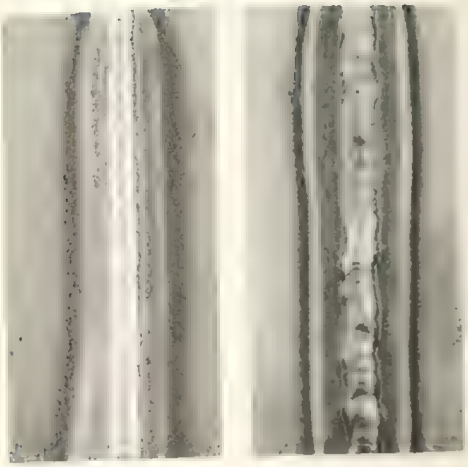


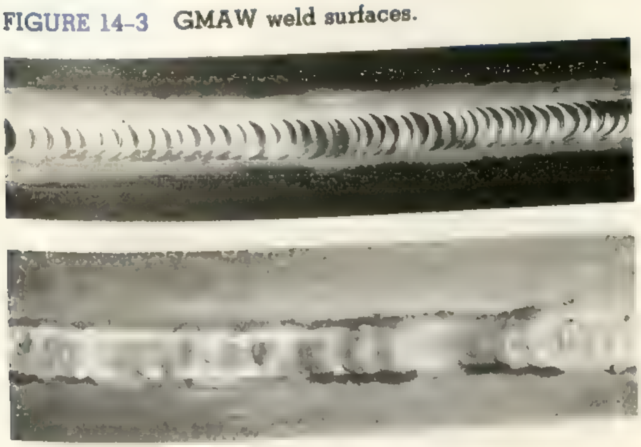
FIGURE 14-2 GTAW weld surfaces.

cient shield and with an inefficient shield. The following factors adversely affect the efficiency of the gas shielding:

1. Insufficient shielding gas due to breezes, low flow rates, and so on
2. Insufficient shielding due to defects of the shielding gas delivery system
3. Impure shielding gas

The most common problem of inefficient shield is due to breezes in the weld area. This is due to open windows and doors and the use of ventilating fans for the welder's personal comfort. The solution is to provide small windbreaks or shields in the arc area. In field welding the welder can use his body to shield the arc area from the breeze. Temporary enclosures are often used for welding high-rise buildings and for pipelines. Shielding gas flow can be increased; however, this may be expensive.

FIGURE 14-3 GMAW weld surfaces.



The welder will immediately notice the deterioration of the weld, which is an indication that shielding efficiency is less than required.

Gas delivery system problems can affect the shielding efficiency. In gas metal arc welding the most prevalent problems are spatter buildup on the gas nozzle, which can greatly impair gas flow, and when using CO_2, it can freeze the regulator, which will stop gas flow. Other problems are broken hoses or loose hose connections within the wire feeder, the welding gun, or at the gas supply cylinder. Inoperative solenoid valves, gun switches, or control relays may also be a problem.

In gas tungsten arc welding spatter buildup is not a problem; instead, leaking hoses, cracked tubing, and loose connections can be the problem. A specific problem is encountered with cable assemblies when water tubes and gas tubes are together; water leaks can get in the gas supply hose and create trouble. Certain kinds of tubing deteriorates in time and should be replaced. Maintenance of the gas supply system should be performed routinely or if there is a suspicion of leaks.

The third factor relates to the purity of shielding gas. In general, this is rarely the problem since gas suppliers maintain constant checks on gas purity. If there is a suspicion that a cylinder has impure gas, it should be switched and a new cylinder used. If there is still a suspicion of the gas, the gas supplier can make measurements to determine the gas purity. In general, the purity problem relates to moisture in the gas. The specifications for gases include the minimum dew point temperature, which relates to moisture in the gas. It can be measured with portable instruments and can be related to the standard. Dew point is covered more thoroughly in the section on carbon dioxide gas. If this is a problem, and it can be in some tropical countries, an in-line filter can be utilized. These have replaceable elements which must be replaced as they are used.

Gases for Shielding

Argon Argon has no color, odor, or taste and is relatively plentiful compared to the other inert gases. A million cubic feet of air contain 93,000 ft^3 of argon. It is separated from air by liquefying the air under pressure and low temperatures and is then allowed to evaporate by raising the temperature. The argon boils off from the liquid at a temperature of $-302.6°F$ ($-184°C$). For welding the purity of argon is approximately 99.99%. Argon is relatively heavy, approximately 23% heavier than air. It is used as a shielding medium for gas tungsten arc welding and for gas metal arc welding of nonferrous metals. Argon has a relatively low ionization potential. The arc voltage of the gas tungsten arc in argon is lower than in helium. The welding arc tends to be stable in argon, and for this reason it is used in many shielding gas mixtures. Argon is nontoxic but can cause asphyxia-

tion in confined spaces by replacing the air. Argon is specified by Military Specification MIL-A-18455B.

Helium Helium is the second lightest gas. It is one-seventh as heavy as air. It is inert, has no color, odor, or taste, and is nontoxic. In liquid form it is the only known substance to remain fluid at temperatures near absolute zero. Helium is obtained from natural gas and in the Texas fields it represents 2% of the volume. It is found in natural gas in Canada and the USSR. Helium has the highest ionization potential of any of the shielding gases, and for this reason a gas tungsten arc in helium has an extremely high arc voltage. Because of this, arcs in an atmosphere of helium produce a greater amount of heat. Helium's light weight causes it to float away from the arc zone, thus producing an inefficient shield unless higher flow rates are employed. For overhead welding, this can be helpful. It is often mixed with other gases for gas metal arc welding. Helium is expensive for welding and is sometimes in scarce supply. Helium is specified by Federal Specification 88-H-11688.

Carbon Dioxide Carbon dioxide is a compound of about 27% carbon and 72% oxygen. It is made of two oxygen atoms joined with a single atom of carbon. At normal atmospheric temperature and pressure it is colorless, nontoxic, and does not burn. It has a faintly pungent odor and a slightly acid taste. It is about 1½ times heavier than air, and in confined spaces it will displace the air. At elevated temperatures it will disassociate into oxygen and carbon monoxide. In the welding arc, disassociation takes place to the extent that 20 to 30% of the gas in the arc area is carbon monoxide and oxygen. Thus CO_2 has oxidizing characteristics in the welding arc. As the carbon monoxide leaves the arc area, it quickly recombines with oxygen to form CO_2. Extensive measurements have been made and it has been found that the carbon monoxide level at a distance of 7 in. (175 mm) from the welding arc is 0.01% or 100 ppm, which is regarded as a safe limit for carbon monoxide gas. At a distance of 12 in. from the arc the carbon monoxide concentration is 0.005%. A concentration of 5000 ppm of carbon dioxide is considered a safe level. Ventilation should be provided to keep the CO_2 level below this concentration.[1]

Carbon dioxide can exist simultaneously as a solid, a liquid, and a gas at its triple point. At atmospheric pressure solid CO_2 (dry ice) transforms directly to a gas without passing through the liquid phase; that is, it sublimes. At temperatures and pressures above the triple point and below 87 °F in a closed cylinder, carbon dioxide liquid and gas exist in an equilibrium. This is normally the way it occurs in high-pressure cylinders.

Carbon dioxide is manufactured from flue gases, given off by burning natural gas, fuel oil, or coke. It is also obtained as a by-product of the calcination operation of lime kilns, from the manufacturing of ammonia, and from the fermentation of alcohol. The CO_2 gas is cleaned, purified, and dried before packaging. The purity of carbon dioxide gas can vary considerably depending on the process of manufacture. The federal specification covers two classifications of CO_2. Grade B, nonmedical, type 1, with very little moisture content for special uses, covers welding-grade CO_2. The purity specified for welding-grade CO_2 gas is a minimum dew point temperature of −40° (−40 °C). Figure 14-4 shows the dew point of CO_2 versus the percent of moisture in the gas. The standard provides a minimum dew point of −40 °F (−40 °C); however, many manufacturers produce welding-grade CO_2 gas with a dew point temperature as low as −70 °F (−57 °C). This gas has a moisture content of 0.0091% by weight and/or 9 parts per million (ppm). Dew point can be measured using portable instruments to determine if the gas meets its standard. Too much moisture in the gas will cause weld porosity. CO_2 is covered by Federal Specification BB-C-101A.

Dew Point °F	Dew Point °C	% Moisture by Weight	ppm Moisture in CO_2
−90	−68	0.00021	2
−80	−62	0.00043	4
−70	−57	0.00091	9
−60	−51	0.00188	19
−50	−46	0.00365	36
−40	−40	0.0066	66
−30	−34	0.0120	120
−20	−29	0.0218	218
−10	−23	0.0354	354
− 0	−17.8	0.0590	590
10	−12.2	0.0980	980

FIGURE 14-4 Dew point versus percentage of moisture in CO_2.

Welding with the Different Gases

The composition of the gas shielding envelope can be a single or pure gas; a mixture of two gases, known as duplex mixtures; or a mixture of three gases, known as tri-mix gases. Mixtures can combine inert and active gases.

For gas tungsten arc welding, inert gases normally are used only for shielding. Mixtures employing a small amount of an active gas are sometimes used. Mixtures of two inert gases are often used, and sometimes a reducing gas is included.

When welding with the gas metal arc process, the pure inert gases do not provide good arc characteristics when welding steel. However, pure CO_2 does provide good arc characteristics. For GMAW, argon with small amounts of oxygen improves the penetration pattern, bead contour, and eliminates undercut due to the wetting action. Argon with carbon dioxide is a popular mixture for welding steels. The triple-mix gases, usually argon

with CO_2 and oxygen, or argon with CO_2 and helium, have specific advantages to be mentioned later.

It is important to select the correct gas mixture when using gas tungsten arc or gas metal arc welding and for welding the particular base metal involved. Following is a review of the gases and gas mixtures and their use for shielding in arc welding.

Argon Plus Oxygen For gas tungsten arc welding, very small additions of oxygen, less than 1%, helps to stiffen the arc. Oxygen is used for direct-current electrode negative (DCEN) of aluminum. It is also used for thin steels, including stainless steels.

With gas metal arc welding, arc transfer characteristics are strongly influenced by the shielding gas composition. In mixtures the amount of current needed to reach the transition point diminishes as the percent of CO_2 decreases. The poor bead contour and penetration pattern obtained with pure argon are improved with the addition of oxygen. Oxygen is normally added in amounts of 1 to 2%, or 3 to 5%. This provides for spray transfer. The amount of oxygen is limited to 5%. The weld bead profile is shown in Figure 14-5. The more oxidizing the shielding gas, the more important it is to select a welding electrode that contains sufficient deoxidizers to overcome the loss of silicon, manganese, and aluminum. More oxygen would lead to the formation of porosity in the deposit. Oxygen improves the penetration pattern by broadening the deep penetration finger at the center of the weld. It also improves bead contour and eliminates the undercut at the edges of the weld, due to better wetting action.

Argon Plus Helium Gas tungsten arc welding uses argon–helium mixtures for welding nonferrous metals. The addition of helium in percentages of 50 to 75% raises the arc voltage and increases the heat in the arc. It is particularly useful for welding heavy thicknesses of aluminum, magnesium, and copper, and for overhead-position welding. With the higher percentages of helium the speed and quality of alternating-current welding of aluminum is improved. The 25% argon–75% helium mixture is used for the gas tungsten hot wire variation. The argon plus helium mixture is also used for gas metal arc welding of nonferrous metals.

Argon Plus Hydrogen Argon with the addition of small amounts of hydrogen increases the arc voltage and increases the heat in the arc. Mixtures of argon containing up to 5% hydrogen are used for welding nickel and nickel alloys and for welding heavier sections of austenitic stainless steels. Mixtures of argon with up to 25% hydrogen are used for welding thick metals that have high heat conductivity, such as copper. It has an advantage in high-speed automatic welding. Hydrogen additions cannot be used for welding mild or low-alloy steels due to problem of hydrogen pickup. Hydrogen should not be used with aluminum and magnesium.

Argon Plus Nitrogen In some countries pure nitrogen is used for gas tungsten arc welding copper. The quality of the resulting welds is not as good as desired. Adding 50 to 75% argon to nitrogen produces a higher-quality weld. Nitrogen is not used as a shielding gas in North America.

Argon Plus Carbon Dioxide Argon plus carbon dioxide is not used for gas tungsten arc welding. For gas metal arc welding one of the most popular mixtures is 75% argon and 25% CO_2. However, outside North America the more popular mixture is 80% argon and 20% CO_2. It is widely used on steel in the thinner thicknesses, where deep penetration is not necessary and where bead appearance is important. It provides improved appearance over 100% CO_2. Spatter is greatly reduced. It is also helpful for out-of-position welding, on thin sheet metal, and when fitup is poor.

Carbon Dioxide One hundred percent carbon dioxide shielding produces broad, deep-penetration welds. Bead contour is good and there is no tendency toward undercutting. Compared to inert gases, CO_2 is relatively inexpensive. The chief drawback of CO_2 shielding is the tendency for the arc to be somewhat violent. This can lead to spatter and makes welding of thin materials difficult. This is the reason for the argon–CO_2 mixtures. Carbon dioxide should not be used for gas tungsten arc welding. CO_2 is commonly used for flux-cored arc welding.

Tri-mixed Gases Shielding gases containing three gases are becoming more popular. Normally, the mixtures utilize argon with oxygen and CO_2, and sometimes argon, CO_2, and helium. In the liquefication of argon, the raw argon contains about 2% oxygen before final purification. The impure argon is then mixed with CO_2, which provides a tri-mix of 70% argon, 2% oxygen, and the remainder CO_2. This mixture is popular for welding steels. Another tri-mix adds a small amount of helium to the argon–CO_2 mixture. This tends to increase the arc voltage and provide higher deposition rates.

Various other mixtures of gases are becoming available which have specific features or advantages. Gas sup-

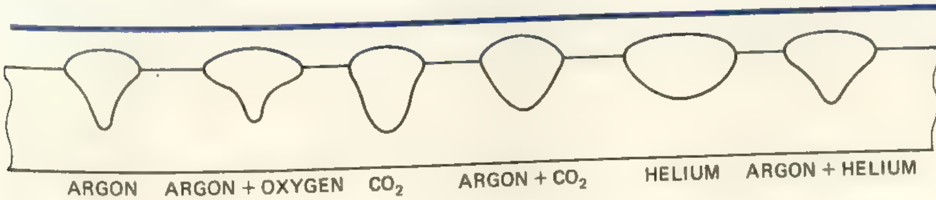


FIGURE 14-5 Shielding gas related to weld profile—DCFP.

pliers provide specific compositions and applications. This includes high-performance shielding gas mixtures that provide higher deposition rates or higher travel speeds. Most of these gases are three-component mixtures that contain helium. Use of these gases increases the arc voltage, and in many cases the user is expected to use a longer wire stickout, increasing the I^2R heating of the welding electrode beyond the tip. The higher voltage and the extended electrode wire increase the energy in the arc and increase deposition rates. Proprietary shielding gases of this type are TIME gas, Stargon gas, and others. The gas suppliers claim improved weld deposit properties. It is wise to investigate these gases thoroughly under laboratory and production conditions. Laboratory tests should obtain all data and compare improved deposition or travel speed versus the extra cost of the gas.

Figure 14-6 summarizes the more popular shielding gas mixtures.

14-2 FUEL GASES FOR WELDING AND CUTTING

Oxygen and sometimes air is used with various hydrocarbon fuel gases for producing heat by means of chemical combustion. These fuel gases, usually with oxygen, are used for soldering, brazing, welding, oxygen cutting, flame spraying, flame hardening, and flame straightening. The major fuel gases are acetylene, natural gas, liquid petroleum gases (propane and propylene), and synthetic gases such as methylacetylene propadiene. The only fuel gases used for welding are compounds of carbon and hydrogen which will react with oxygen to produce a flame having a temperature above the melting point of most metals. Nonhydrocarbon fuel gases should not be used for welding since their products of combustion are toxic.

The fuel gas–oxygen reaction is in two steps. The primary reaction produces carbon monoxide and hydrogen plus heat:

$$\text{fuel gas} + O_2 \rightarrow CO + H_2 + \text{heat}$$

The secondary reaction, which utilizes oxygen from the air, will oxidize the carbon monoxide and hydrogen to carbon dioxide and water vapor plus additional heat:

$$\text{Air} + CO + H_2 \rightarrow CO_2 + H_2O + \text{heat}$$

This complete combustion reaction produces a large amount of heat known as the gross heat of combustion

FIGURE 14-6 Summary of shielding gases and mixtures and their use (North America).

Shielding Gas	Gas Reaction	GMAW and FCAW	GTAW and PAW
Pure Gases			
Argon, Ar	Inert	Nonferrous	All Metals
Helium, He	Inert	Nonferrous	Al, Mg, and copper and alloy
Carbon dioxide, CO_2	Oxidizing	Mild and low-alloy steels some stainless steels	Not used
Two-Component Mixtures			
Argon mixtures			
Argon + 20–50% helium	Inert	Al, Mg, and Cu and alloys	Al, Mg, and Cu and Alloys
Argon + 1–2% CO_2	Oxidizing	Stainless and low-alloy steels	Not used
Argon + 3–5% CO_2	Oxidizing	Mild, low-alloy, and stainless steels	Not used
Argon + 20–30% CO_2	Slightly oxidized	Mild and low-alloy steels some stainless steels	Not used
Argon + 2–4% He	Reducing	Not used	Nickel and alloy and Austinetic SS
Helium mixtures	—	Al and Alloys, Cu and alloys	Al and alloys, Cu and alloys
Helium + 25% argon	Inert		
CO_2 mixtures			
CO_2 + up to 20% O_2	Oxidizing	Mild and low-alloy steels (used in Japan)	Not used
CO_2 + 3–10% O_2	Oxidizing	Mild and low-alloy steels (used in Europe)	Not used
Three-Component Mixtures			
Helium mixtures			
Helium + 75% Ar + 25% CO_2	Inert	Stainless steel and low-alloy steels	Not used
Argon mixtures			
CO_2 + 3–10% O_2 + 15% CO_2	Oxidizing	Mild steels (used in Europe)	Not used

(heat of primary reaction plus heat of secondary reaction). This is given in Btu per pound of fuel gas or Btu per cubic foot of fuel gas or calories.

The properties of fuel gases are given in Figure 14-7. The figure shows the flame temperatures of each of the fuel gases in oxygen and in air. Flame temperature in oxygen is always much higher than in air. The flame temperature and heat of combustion are indications of the amount of work that can be done by the different fuel gases. However, when comparing the cost of using different gases it is also important to consider the ratio of fuel gas to oxygen required for combustion. This is neccessary so that the cost of both the fuel gas and the cost of oxygen are combined to obtain the total gas cost. These data are theoretical since in actual use a portion of the oxygen required for total combustion comes from the air surrounding the flame. For example, the combination of acetylene and oxygen for the primary reaction is a 1:1 ratio. The additional oxygen required for the secondary reaction requires 1.5 units of extra oxygen; therefore, the total ratio of oxygen to acetylene is 2.5 rather than 1. This is determined by working out the chemistry of both the primary and secondary reactions. The primary reaction is produced in the inner cone and the secondary reaction in the outer envelope of the flame.

Another important consideration in selecting fuel gas is its specific gravity. Hydrogen is the lightest in weight of all gases. Propane, propylene, and methylacetylene are all heavier than air. Acetylene is slightly lighter than air. Methane and natural gas are slightly over half the weight of air. This shows that some of the fuel gases would tend to float away into the atmosphere while others would collect in low spots, in enclosed areas of weldments, or in pits and bottoms of tanks. This is a very important safety consideration since fuel gas leakage can occur

Another safety factor is the flammability limits in air. Acetylene will burn in air with a minimum of 2.5% to a maximum of 81%. This is the widest range of any fuel gas; however, hydrogen is almost as wide. The other gases are much lower. This means that acetylene is the most dangerous, since it will ignite in any percentage with air between these two limits. Figure 14-7 also shows the threshold limit values (TLV) of the different gases.[1]

Acetylene (C_2H_2)

Acetylene is a compound of carbon and hydrogen. It is a colorless flammable gas slightly lighter than air. Acetylene of 100% purity is odorless, but gas of commercial purity has a distinctive garlic flavor. Acetylene burns in air with an intensely hot, yellow, luminous, and smoky flame. For safety reasons acetylene is never compressed above 15 psi (0.0105 kg/mm²). Acetylene cylinders are made safe by providing a porous mass of material inside the cylinder which is saturated with acetone. Acetylene dissolves in acetone and in this mode can be compressed to 250 psi (0.1750 kg/mm²) without danger.

Acetylene with oxygen produces the highest flame temperature of any of the fuel gases. It also has the most concentrated flame, but it produces less gross heat of combustion than the liquid petroleum gases and the synthetic gases. Acetylene is manufactured by the reaction of water and calcium carbide. This is sometimes done at plant sites in acetylene generators. Acetylene is nontoxic; however, it is an anesthetic and if present in sufficiently high concentration it is an asphyxiant in that it replaces oxygen and will produce suffocation.

Hydrogen (H_2)

Hydrogen is the lightest gas and is present in the atmosphere in concentrations of about 0.01% at lower altitudes. Hydrogen may also be present in the arc area from water vapor resulting from the products of combustion and also from high temperature reaction with hydrocarbons that might be present. Hydrogen is soluble in molten steel but the solubility of hydrogen at room temperature is very low. As molten weld metal cools and solidifies the hydrogen is rejected from the solution and becomes entrapped in the solidifying weld metal. It will collect at grain boundaries or at discontinuities of any type where it will create high pressures, which in turn cause high stresses within the weld. These pressures and stresses lead to minute cracks in the weld metal which can develop into larger cracks. The small concentrations of hydrogen that appear on the fractured surface are known as fish eyes because of their characteristic appearance. Hydrogen also causes underbead cracking in the heat-affected zone. Hydrogen will, however, gradually escape from the solid steel over a period of time. This migration of hydrogen from the weld metal is accelerated if the temperature of the metal is increased.

Hydrogen can be used as a fuel gas and originally was an important commercial fuel gas. Its flammable limits in air range from 4 to 75%. When hydrogen is burned in either oxygen or air the flame temperature is lower than that of acetylene. It requires less oxygen for complete combustion but does not produce sufficient gross heat of combustion for industrial welding.

Methane (CH_4)

Methane is a colorless, odorless, tasteless, flammable gas. It is generally considered nontoxic, and concentrations of up to 9% can be inhaled without apparent ill effects. Methane is the major component of natural gas. It is normally separated from natural gas and can be obtained from petroleum. It is normally shipped and stored in high-pressure gas cylinders. It can, however, be shipped in liquid form in special insulated tanks at temperatures

FIGURE 14-7 Properties of fuel gases.

Property	Acetylene	Hydrogen	Methane	Methyl Acetylene Propadiene	Propane	Propylene	Natural Gas
International symbol and cylinder marking	C_2H_2	H_2	CH_4	$CH_3C{:}CH$ (MPS)	C_3H_8 (LP Gas)	C_3H_6 (PRY)	MET
Molecular weight	26.036	2.016	16.042	40.07	44.094	42.078	Similar to Methane
Specific gravity of gas (Air = 1)	0.91	0.069	0.55	1.48	1.56	1.48	0.56
Specific volume of gas (at 60 °F and 1 atm) cu ft/lb	14.5	192.0	23.6	8.85	8.6	9.5	23.6
Specific gravity of liquid	–	–	–	0.576	0.507	0.527	–
Lb./gal of liquid @ 60 °F	–	–	–	4.80	4.25	4.38	–
Density of gas–lb/cu ft	0.0680	0.0052	0.0416	0.113	0.115	0.105	0.0424
Boiling point (at 1 atm)							
°F	–119.2	–422.9	–258.6	–9.6	–43.8	–53.9	–161
°C	–84	–252	–161	–23.1	–42.1	–47.7	–107
Flame temperature (neutral)							
in oxygen °F	5600	4800	5000	5300	4600	5250	4600
in oxygen °C	3100	2650	2775	2925	2550	2900	2550
in air °F	4700	4000	3525	3200	3840	3150	3525
in air °C	2600	2200	1950	1760	2100	1730	1950
Ratio of oxygen to fuel gas required for combustion	1 to 1	.5 to 1	1.75 to 1	2.5 to 1	3.5 to 1	4.5 to 1	2 to 1
Ratio of air to fuel gas required for combustion	11.9	2.38	9.52	21.83	24.30	21.83	10.04
Gross heat of combustion							
Btu per pound	21,600	52,800	23,000	21,000	21,500	22,000	24,000
Btu per cubic feet	1,500	344	1,000	2,500	2,500	2,400	1,000
Flammable limits in air (by volume)	2.5 to 81%	4 to 75%	5.3 to 15%	2.4 to 11.7%	2.2 to 9.5%	2.0 to 10.3%	5.3 to 14%
Max allowable concentration in TLV's	Non toxic asphyxiant	Non toxic asphyxiant	Non toxic up to 9%	Non toxic 1000 PPM	Non toxic asphyxiant	Non toxic	Non toxic up to 25%

Note: The shipping containers of these gases would all be marked "Flammable Compressed Gas."

below its boiling point. It acts in the flame in the manner similar to natural gas.

Natural Gas (essentially CH_4)

Natural gas has much the same characteristics as methane. The composition of natural gas varies in different geographical locations and the gross heat of combustion of natural gas varies from one locality to another, but 1000 Btu per cubic foot is normally accepted as a minimum. Natural gas is used in oxygen flame cutting. Its flame temperature is relatively low and the gross heat of combustion is also relatively low. It is less expensive than other fuel gases and for this reason has become quite popular. It is not used for gas welding or flame hardening because of its lower flame temperature. It is normally supplied via pipeline to industrial sites and is sold by the cubic foot.

Liquefied Petroleum Gases

The liquefied petroleum (LP) gases are propane and propylene (propene) and butanes. They are by-products of oil refineries and are flammable, colorless, noncorrosive, and nontoxic. They have an anesthetic effect and when they displace oxygen in the air they act as asphyxiants. This is an important safety factor since they weigh approximately 1½ to almost 2 times the weight of air.

Pure propane is odorless; however, it is given an artificial odorization while propalene has an unpleasant odor characteristic of refineries. The flame temperature of propane is lower than that of acetylene but its gross heat of combustion is higher, more than 1½ times that of acetylene. Propane is available in pure form and as mixtures. The mixtures contain additives such as ethylene, propylene, or ethyl ether, which increase the flame temperature and the heat of combustion. Additives also increase the price of the gas. Propane base gases are known as Acetogen, Chemi-gas, Flamex, Hy-Temp, Chem-O-Lene, and so on.

Propylene has a higher flame temperature than propane but not as high as acetylene. It also has a gross heat of combustion approximately 1½ times that of acetylene. Propylene is also available as pure gas and with additives and is given such trade names as Apachi gas, HPG, B.T.U., and Liquifuel.

The liquefied petroleum gases require considerably more oxygen for combustion than acetylene. They are shipped and stored in the liquefied form in cylinders and tanks. They normally do not have pressures exceeding the 375 psi (0.2625 kg/mm²). The liquefied petroleum vaporizes in the cylinder and is discharged as a gas. It is usually sold by weight. To determine the cubic feet of gas multiply by the specific volume of the gas.

Synthetic Gases: Methylacetylene–Propadiene Stabilized (MPS)

The most popular synthetic hydrocarbon fuel gas is methylacetylene plus propadiene (allene), sometimes called methylacetylene–propadiene stabilized or MPS gas. It is a by-product of the chemical industry. It goes by several trade names, including MAPP gas and Fuel-gas. This gas is colorless, flammable, and slightly toxic. The tentative maximum concentration of 1000 parts per million has been suggested for its TLV. Methylacetylene–propadiene stabilized has a flame temperature in oxygen higher than propane but less than acetylene. Its gross heat of combustion is over 1½ times that of acetylene. It is stored and shipped as a liquefied gas in its own vapor pressure of about 60 psi (0.042 kg/mm²) at 70 °F (21.1 °C). These gases are usually sold by weight and are available in cylinders and in bulk. When using these different fuel gases, different torches and tips are usually required.

Selecting Fuel Gases

The selection of a fuel gas should be based on the gas that will do the best job at the least cost. Necessary properties would include the flame temperature, the gross heat of combustion, and the oxygen-to-fuel gas ratio for combustion. This information is shown in Figure 14-7. Some of the fuel gases can be used only for heating, for oxygen cutting, or for soldering and brazing. They cannot all be used for gas welding or for flame hardening. The uses of a particular gas depend on its flame temperature, heat of combustion, heat distribution in the flame, and coupling distance. All fuel gases can be used for flame spraying; however, for spraying high melting temperature metals the higher flame temperature fuel gases must be used. All fuel gases can be used for heating but the type of heating might dictate the fuel gas. For example, acetylene is a more concentrated heat source than the other gases. Figure 14-8 shows the flame temperatures for the common fuel gases versus the oxygen-to-fuel gas ratio. This is the cubic feet of pure oxygen per cubic foot of fuel gas. The dot on each curve is the temperature of the neutral flame. A neutral flame is used when welding steel. The temperature of all fuel gas flames increases when more oxygen is used.

For underwater oxygen flame cutting, acetylene can be used down to depths of 30 ft, but the methylacetylene–propadiene (MPS) gas can be used to depths of 100 ft. Special torches are required. Selection information is summarized in Figure 14-9.

The ratios of oxygen to fuel gases have an important bearing on the cost of the total operation since oxygen is expensive. The amount of oxygen required is difficult to determine since it depends on the type of torch

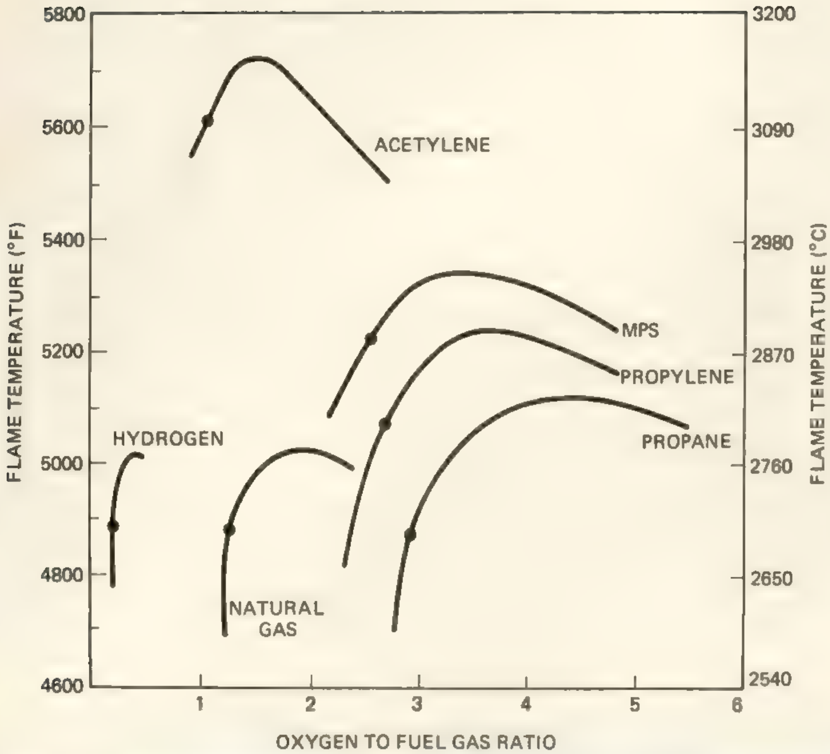


FIGURE 14-8 **Flame temperatures of fuel gases.**

employed. A single flame port torch is used for brazing or welding, and a multiflame port torch is used for flame cutting and heating. Multiport torches have a higher oxygen-to-fuel gas ratio since the inner flames are not able to receive oxygen from the air. Another factor to consider is the heat transfer or coupling. This is best done by the practical test.

The gross heat of combustion is an indication of how much work can be done by a given volume of fuel gas—hence, the amounts of oxygen and fuel gas that are required to do work. The measure of comparison here is to establish welding or cutting procedures which will include gas usage and work travel speeds. This information is available from torch and gas manufacturers. Then calculate the time required for a specific cut or weld and compare the results. It is wise to confirm the calculated times by making tests under controlled conditions. In making cutting speed tests make sure that the most efficient cutting tip is used for the conditions being tested. Differences in tips can be more of a determining factor than differences in gases. Remember that it is the oxygen jet that does the cutting.

It is becoming increasingly important to determine the availability of different fuel gases. As energy sources become more expensive, the cost usefulness relationship can change.

14-3 ATMOSPHERE GASES

The atmosphere that surrounds the earth provides the air we breath and supports life. At sea level its pressure is approximately 14.7 psi (1 bar). Its composition is approxi-

FIGURE 14-9 **Uses of fuel gases.**

Used for:	Fuel Gas				
	Acetylene	LPG Propane	Natural Gas or Methane	MPS	Propylene
Heating	Not preferred	Yes	Yes	Yes	Yes
Torch soldering	Yes (in air)	Yes (in air)	Yes (in air)	Yes (in air)	Yes (in air)
Torch brazing	Yes	Yes	Yes	Yes	Yes
Oxygen cutting	Yes	Yes	Yes	Yes	Yes
Flame spraying	Yes	Yes	Yes	Yes	Yes
Gas welding-steel	Yes	No	No	Marginal	No
Flame hardening	Yes	No	No	Yes	No

mately 78% nitrogen, 21% oxygen, and 1% argon, with small amounts of carbon dioxide, hydrogen, and other inert gases. Nitrogen, oxygen, and argon are obtained by the liquefaction and distillation of air. The properties of these gases are given in Section 14-1.

Oxygen

Oxygen is a colorless, odorless, tasteless gas that supports life and makes combustion possible. Oxygen combines with many elements to form oxides. Oxygen is very active and combines with most metals at room temperatures. Oxygen combines with iron to form compounds which can remain in the weld metal as inclusions. As the molten weld metal cools, free oxygen in the arc area will combine with carbon of the steel and form carbon monoxide. This may be trapped in the weld metal as it solidifies. The gases collect into pockets which cause pores or hollow spaces. This problem is often overcome by providing deoxidizers in the filler metal, such as manganese and silicon. These elements will combine with the oxygen to produce an oxide of manganese or silicon, which will float to the surface of the molten steel.

The purity of high-pressure oxygen supplied in a high-pressure cylinder is 99.6+ by volume. The oxygen used for flame cutting should have this purity. When the purity of oxygen is reduced, the oxidation of the metal being cut is retarded and more oxygen is consumed, cutting speed is reduced, and the cut quality is reduced. It is reported that 1% decrease in oxygen purity decreases cutting speed by 10 to 15%. This reduction in purity also increases the consumption of oxygen by 25 to 35%. To compensate for reduced purity, the pressure is usually increased, which contributes further to poor flame cut surfaces. Oxygen with a purity below 97% should not be used.

Liquid oxygen is extremely cold, −297 °F (−183 °C) at atmosphere pressure. Accidental contact of liquid oxygen will cause severe frostbite to the eyes or skin. Protective clothing and safety goggles or face shield must be worn when handling liquid oxygen.

Combustibles must be kept away from oxygen. Many materials which do not normally burn in air, and other materials which are combustible in air, may burn violently in an atmosphere high in oxygen. All organic materials and flammable substances, such as oil, grease, kerosene, wood, paint, tar, and coal dust, must be kept away from oxygen. An accumulation of oxygen can be hazardous, and therefore proper ventilation is required. Oxygen should *never* be used in place of compressed air.

The Federal Specification BB-0-925A covers oxygen for industrial use. Purity must be 99.5% oxygen or greater.

Nitrogen

Nitrogen is the largest single element in the atmosphere. It is colorless, odorless, flavorless, nontoxic, and is almost an inert gas. Nitrogen does not burn or support combustion. In the arc, or at high temperatures, nitrogen will combine with other gases. It is soluble in molten iron, but at room temperature the solubility is very low. During the cooling and solidification process, the nitrogen collects in pockets or precipitates out as iron nitrites. In very small amounts, nitrites can increase the strength and hardness of steel. In larger amounts, nitrogen can lead to porosity in the weld deposit. The reduction of ductility due to the presence of iron nitrites may lead to cracking of the weld metal. The typical purity of compressed nitrogen is 99.8% by volume. The dew point is approximately −70 °F (−57 °C).

Liquid nitrogen is very cold, −320 °F (−196 °C) at atmosphere pressure. Accidental contact of liquid nitrogen will cause severe burns to the eyes or skin. Protective clothing and safety goggles or face shields must be worn when handling liquid nitrogen. Nitrogen tends to vaporize very easily and an accumulation of nitrogen can be hazardous since it does not support life. The Federal Specification BB-N-411C covers nitrogen of three purities; the minimum is 99.50% nitrogen.

Nitrogen is not a true inert gas and should not be used as a shielding gas for welding steel. Nitrogen is used in some parts of the world for welding copper. It provides an extra-high-temperature arc that is useful in overcoming the high thermal conductivity of copper when using the gas tungsten arc process. Tungsten electrode erosion is very high when using nitrogen. Mixtures of argon and nitrogen produce higher-quality welds than those of nitrogen alone.

Nitrogen is often used for purging stainless steel pipe and tubing systems. It is much less expensive than argon and it keeps the oxygen away from the root side of the weld. Nitrogen is also used for maintaining positive pressures in piping systems during testing and cleaning operations.

14-4 GAS CONTAINERS AND APPARATUSES

The shielding gases and fuel gases must be transported, stored, and available at the point of use. The most convenient way is by portable cylinders which are easily taken to the job site. For installations where a high volume of gas is required the bulk storage system or manufacturing the gas at the site is used. This requires equipment to pipe the gas to the welding or cutting stations. The design of piping systems is complex and should be done only by experts who are familiar with safety regulations and codes. In bulk form, the gas is supplied as a liquid. The capacity of a bulk system is normally between 3000 and 1 million cubic feet (84,950 to 28,310,000 liters).

Carbon dioxide can also be obtained in bulk containers. The bulk system is only used when supplying a

Cylinder Identification	Cylinder Type[a]	Cylinder Contents	Cylinder Capacity[a] (ft^3)	Full Cylinder Pressure at 70°F (psi)	Approximate Weight	
					Full (lb)[a]	Empty (lb)[a]
Nonflammable compressed gas	DOT type 3A or 3AA	Argon	244 330	2200 2640	158 177	133 143
Nonflammable compressed gas	High pressure	Argon + oxygen	330	2640	177	143
Nonflammable compressed gas	High pressure	Argon + carbon dioxide	379	2640	177	143
He nonflammable compressed gas	High pressure	Helium	213	2200	135	133
Hydrogen flammable compressed gas	High pressure	Hydrogen	191	2015	134	133
O_2 nonflammable compressed gas	High pressure	Oxygen	330 244	2640 2200	172 153	146 133
CO_2 non-flammable compressed gas	Medium pressure	Carbon dioxide liquid + gas	435	1000	183	133
LPG or LP gas or PRY or MAPP	DOT B 240	Liquid under vapor pressure	Varies by gas and supplier	94	Varies by gas and supplier	Varies by gas and supplier
C_2H_2 flammable compressed gas	DOT 8 AL	Acetylene disolvent in acetone	390	250	207	180

[a]The cylinder capacity and weights will vary by supplier.

FIGURE 14-10 High pressure gas cylinder types and sizes.

large number of welding stations and where usage will justify the bulk system.

There are four basic types of cylinders used for transporting welding gases (Figure 14-10). In addition, these types of cylinders come in different sizes according to the gas producer. These high-pressure cylinders are commonly used for transporting and storing argon, oxygen, hydrogen, nitrogen, and helium. This same type of cylinder is used for mixtures of these gases and mixtures of argon with CO_2. The cylinder of this type is shown in Figure 14-11. These cylinders are made under very strict manufacturing procedures and are covered by various laws. In the United States, the Department of Transportation provides the regulations. They are made of manganese steel (3A) or chrome molybdenum steel (3AA) and each must be inspected, numbered, and reinspected at regular intervals, usually every five years.[2] Typical cylinder markings are shown in Figure 14-12.

There are no uniform standards for cylinder sizes even though different gas companies offer standards within their own organization. There is no standard color code in the United States for the industrial gases. Some gas producers have standardized cylinder color codes within their own organization, however. There is a standardized identification system. Either the total name of the gas or the international symbol of the gas is required on each cylinder. Each cylinder must carry a label showing the hazardous classification of the gas. This information is given in the two charts showing the properties of the gases.

The valve connections of the different gas cylinders have been standardized so that regulators for the same gas can be readily attached to cylinders supplied by different gas producing companies. These standards apply to North America only.

Carbon dioxide (CO_2) welding-grade gas is available in high-pressure steel cylinders. Cylinders containing CO_2 are always labeled "CO_2" and may be labeled "welding grade." They are usually aluminum colored but no standard color code exists.

The standard welding-grade carbon dioxide cylinder (Figure 14-13) contains approximately 50 lb (22.7 kg) or 435 ft^3 (12,317 liters) of carbon dioxide under a pressure of 1000 psi (0.7 kg/mm²). In the CO_2 cylinder, at 70°F (21.1°C) the carbon dioxide is in both a liquid and a vapor form. The liquid carbon dioxide takes up approximately

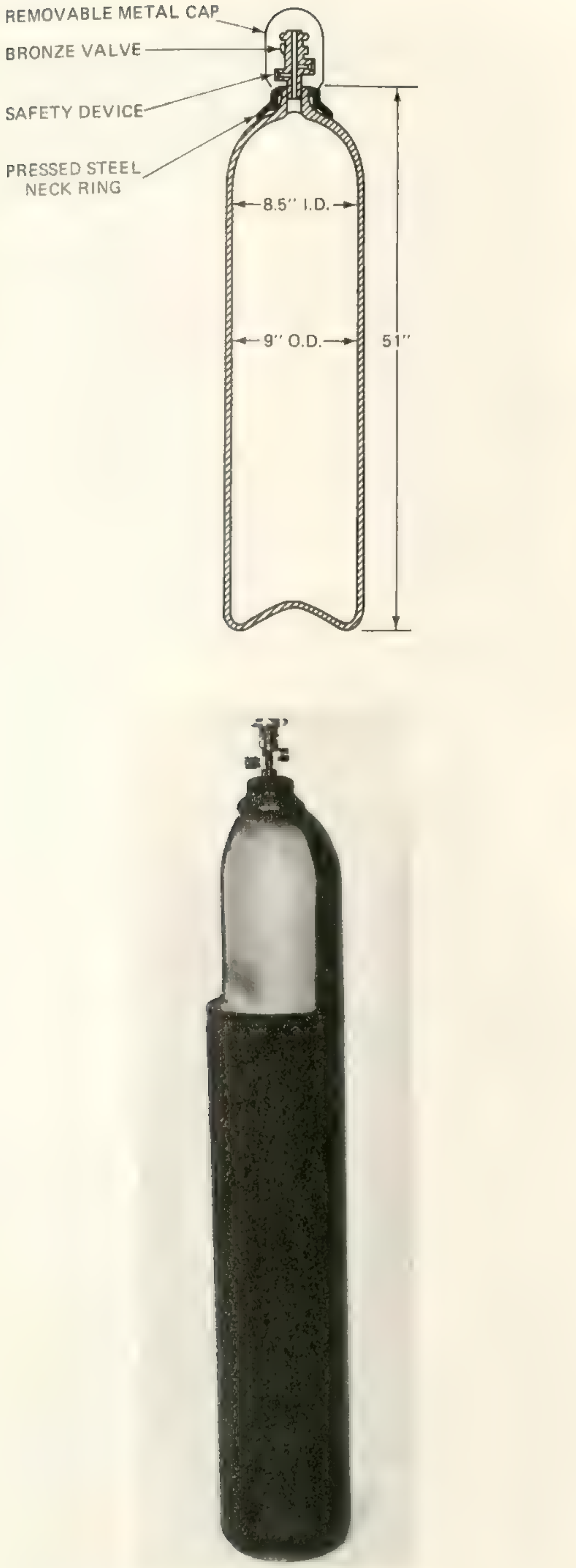
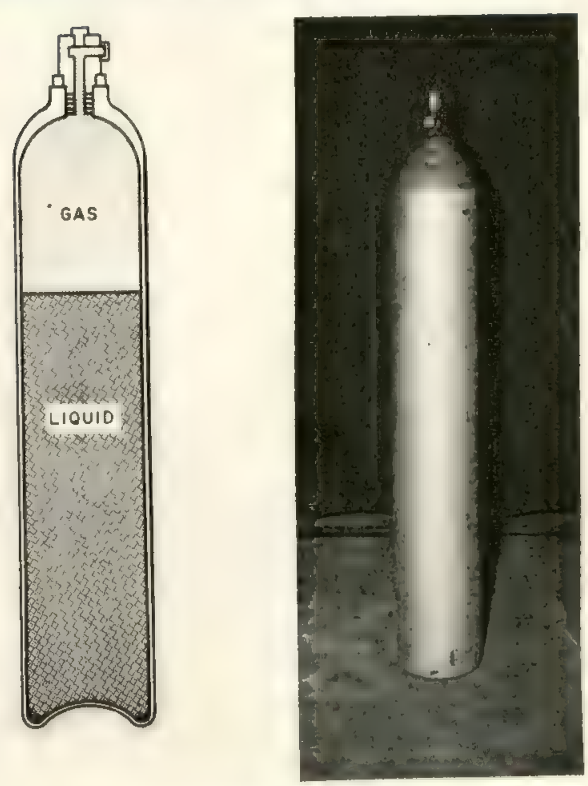


FIGURE 14-11 High-pressure gas cylinder.

two-thirds of the space in the cylinder. Above the liquid the CO_2 exists as a gas. As the gas is drawn from the cylinder, the liquid carbon dioxide vaporizes to replace it. The normal discharge rate of the CO_2 cylinder is from about 4 to 30 ft^3/hr (2 to 14 liters/min). However, a maximum discharge rate of 25 ft^3/hr (12 liters/min) is normally recommended when welding using a single cylinder. In a cold environment, the discharge rate is reduced. As the CO_2 vapor pressure drops from the cylinder pressure to discharge pressure through the CO_2

FIGURE 14-12 Typical number markings on a high-pressure cylinder.

FIGURE 14-13 Cylinder for carbon dioxide.



regulator, it absorbs heat. If flow rates are set too high, this absorption of heat can lead to freezing of the CO_2 regulator. When this happens, the gas shield is interrupted and weld porosity will result. When flow rates higher than 25 ft³/hr (12 liters/min) are required, normal practice is to manifold two CO_2 cylinders in parallel or to place a heater between the CO_2 cylinder and the pressure regulator. As the carbon dioxide gas is drawn from the cylinder it is replaced with carbon dioxide that vaporizes from the liquid. As the liquid carbon dioxide is used, a drop in pressure will be indicated by the pressure gauge. When the pressure in the cylinder has dropped to 200 psi (0.1400 kg/mm²) the cylinder should be replaced with a new one. A positive pressure should always be left in the cylinder to prevent moisture and other contaminants from entering. The valve should be closed.

Pressure is not an accurate measurement of cylinder contents and a partialy used CO_2 cylinder should be weighed to determine how much CO_2 it still contains. To do this, weigh the cylinder then subtract the *tare weight* (weight of cylinder when empty). Tare weight is usually stenciled on the cylinder neck. This gives the weight of the contents. At 70°F, there are 84.7 ft² of CO_2 per pound.

The liquefied petroleum gases are transported and stored in a different type of cylinder, one that is made to handle materials at a lower pressure. They are usually larger since the pressure is not so high. They are made to DOT specification B240 and are similar to the high-pressure cylinders except that they are usually larger in diameter.

When a gas is confined to a specific volume, the pressure exerted on the walls of the cylinder will vary in direct proportion with the temperature. Estimating the volume of gas remaining in a cylinder on the basis of gauge pressure is possible only within very broad limits. This is especially true of the liquefied gases.

Acetylene is transported and stored in a very special type of cylinder (Figure 14-14). This type of cylinder made to DOT specification 8AL is used only for acetylene. As mentioned previously, it is filled with a porous material soaked with acetone and the acetylene is dissolved in the acetone.

Where users have a shielding gas or oxygen demand of 10,000 to 20,000 ft³ per month, cryogenic liquid cylinders can be used (Figure 14-15). Cryogenic liquid cylinders are used for argon, carbon dioxide, nitrogen, and oxygen. The advantage of the cryogenic cylinder is that one cryogenic cylinder is equivalent to 15 to 24 high-pressure cylinders and they operate at a lower pressure. The cryogenic cylinders come in several sizes from different vendors but are all larger than high-pressure cylinders. They are approximately 20 or 24 in. in diameter and about 60 to 66 in. high. When empty they weigh between 250 and 280 lb; when filled they can weigh up to 700 lb. The cryogenic liquid cylinders are basically

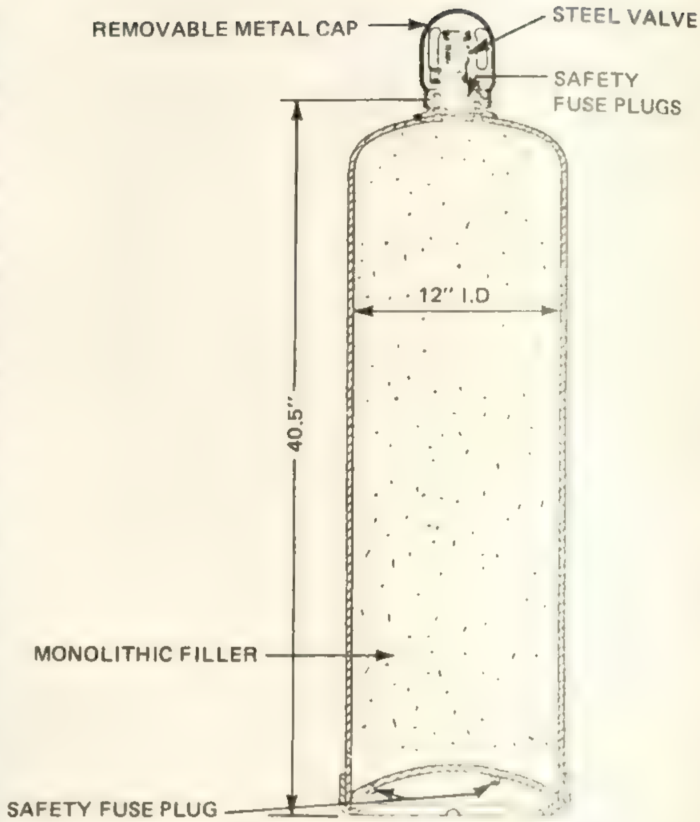


FIGURE 14-14 Cylinder for acetylene.

FIGURE 14-15 Cryogenic cylinder.

insulated vacuum bottles. The gas is stored as a liquid but is vaporized when it is withdrawn. The withdrawal rate can be as high as 250 ft³/hr. The service pressure is approximately 200 psi. Cryogenic liquid cylinder data are shown in Figure 14-16. The hose connectors on cryogenic tanks are the same for the same gas as for high-pressure cylinders.

For fuel gas usage exceeding the output of a single cylinder, the cylinders are manifolded together (Figure 14-17). Usually, flexible tubing is used to connect each cylinder to a manifold which feeds the pipeline. In this way higher rates of gas can be supplied for multiple-torch flame cutting operations or similar.

Apparatus

Various pieces of apparatus are required to utilize gas from high-pressure cylinders. These include regulators and flowmeters or combination units. The gas regulator was described previously. Their function is to reduce pressure and provide constant gas flow. Regulators must only be used for the gas for which they are designed.

The *flowmeter*, sometimes called a *rotometer*, contains two components, the adjustable needle valve which allows for accurate control of gas flow and a slightly tapered transparent tube which contains a float or indicator (Figure 14-18). The gas enters the flowmeter through the needle valve and then passes upward through the tapered tube. As it passes upward the tube becomes enlarged and the float is suspended in the stream of gas. The higher the flow rate the higher the float will rise in the calibrated tube. The tapered tube is calibrated in either cubic feet per hour or liters per minute. It is important that the flowmeter used is designed for the gas being measured. Different float weights are used for gases of different specific gravities. For extremely accurate work the discharge head or the resistance of the gas system beyond the flowmeter must be standardized and related to the calibration of the flowmeter. A typical flowmeter attached to a cylinder is shown in Figure 14-19. The flowmeter should be installed with the tube absolutely vertical for accurate measurement.

Permanent or orifice-type flowmeters can also be used; however, they are not adjustable and are installed in the line following the regulator to establish a specific flow rate of a specific gas. These are used when adjustments are not required.

Check valves are a safety device used to protect welding installations from the dangers of flashback and reverse flow. They prohibit a flashback in the torch from reaching the supply cylinders. These are spring-loaded valves with rubber or neoprene actuators. With normal flow the check valve is open; however, if pressure from the downside exceeds flow pressure, the check valve will close. They are relatively inexpensive and should be used at every installation.

Gas Flow Rates

The flow rates required with the various shielding gases depend on the density or specific gravity of the gases. Welding procedures will provide the flow rates to be used.

When siphon tube CO_2 cylinders are used, external heaters are required. These cylinders are equipped with a plastic siphoning tube extending to the bottom of the cylinder that discharges liquid CO_2 rather than

Gas	Liquid Capacity[a] (Gallons)	(Liters)	Product Weight[a] lb	(kg.)	Gas Capacity (ft³)
Argon	47.6	180	480	218	4.797 @ 235 psi
Carbon dioxide	47.6	180	418	190	3.545 @ 350 psi
Nitrogen	47.6	180	294	133	4.052 @ 235 psi
Oxygen	47.6	180	415	188	5.010 @ 235 psi

[a]Cylinder capacity and weight will vary by supplier.

FIGURE 14-16 Cryogenic liquid cylinder data for 45-gallon type.

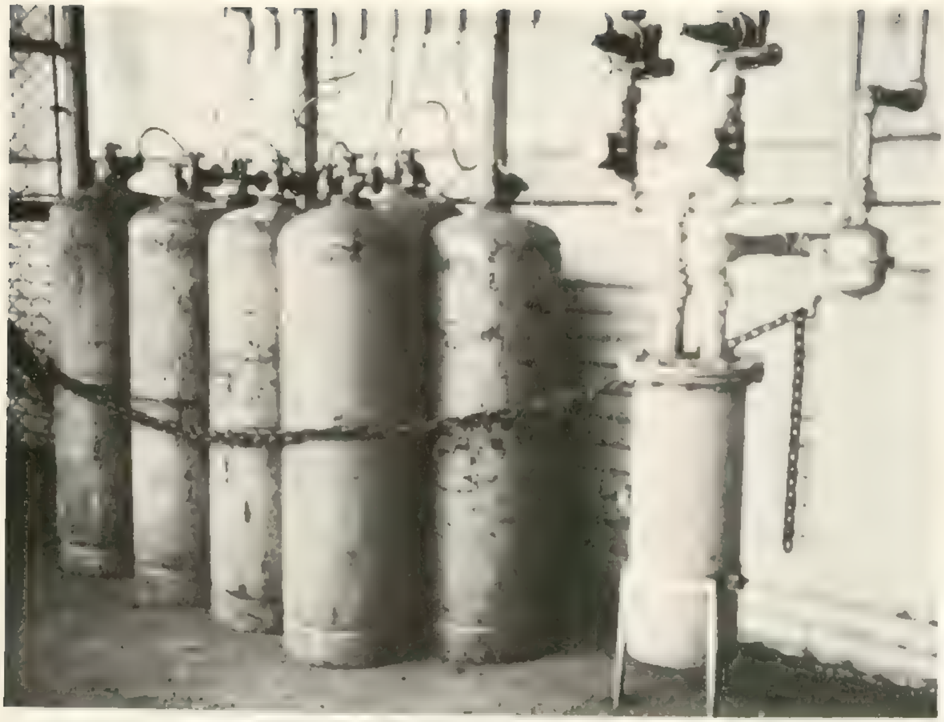


FIGURE 14-17 Manifolding cylinders for pipe distribution system.

gaseous CO_2. The liquid must be vaporized in a heater prior to use. Siphon tube CO_2 cylinders are not popular in the United States, although they can be obtained on special order. They are used in Europe and in other parts of the world.

The final element in the system is the hose leading from the cylinder to the torch or to the control panel. Different types of hose are available, including rubber and various plastic materials. Each type has different characteristics with respect to pressure and the ability to maintain purity of the gas in the cylinder to the arc. It is best to check manufacturers' literature for this information.

Finally, there are such items as proportioners or mixers which can be used to mix different gases together for a particular application. These are involved and should be used based on the manufacturer's recommendations.

FIGURE 14-18 Diagram of gas flow meter.

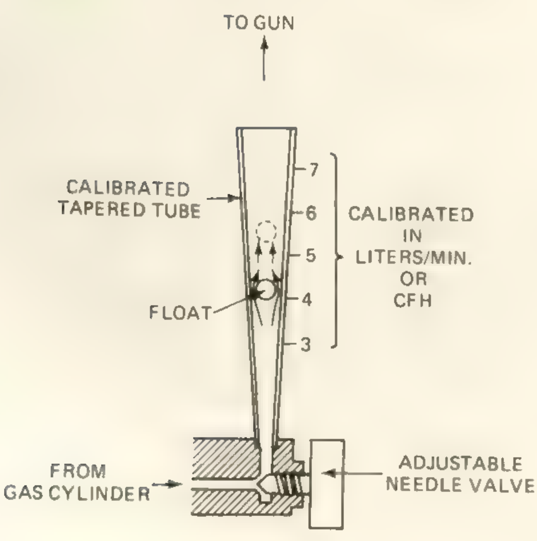
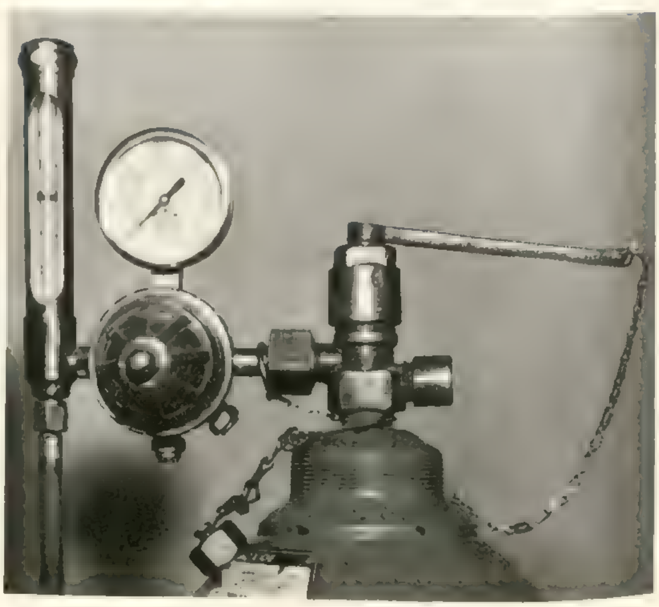


FIGURE 14-19 Gas flow meter.



QUESTIONS

14-1. What is the most common inert gas used for shielding?

14-2. Are mixed inert gases used for shielding?

14-3. What is the purpose of argon–oxygen for shielding gas?

14-4. What is the advantage of argon–CO_2 shielding gas on steel?

14-5. Why should active gases be used on aluminum?

14-6. Why is the density of a shielding gas important?

14-7. What happens to CO_2 in an arc? Away from the arc?

14-8. How is CO_2 gas specified? How is moisture checked?

14-9. What types of gases are used for GTAW welding?

14-10. Name the different fuel gases in use.

14-11. What fuel gas produces the highest flame temperature?

14-12. Does excess oxygen in the flame increase or decrease flame temperature?

14-13. What is the danger of fuel gases that are heavier than air?

14-14. What is the most abundant gas in the atmosphere?

14-15. Why is a higher-than-normal amount of oxygen dangerous?

14-16. What happens in oxygen flame cutting if the oxygen purity is low?

14-17. Describe the different types of tanks used for transporting welding gases.

14-18. Why are cryogenic cylinders of gas used?

14-19. Explain the principle of operation of a flowmeter.

14-20. What is the purpose of a check valve?

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1. "Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment," American Conference of Governmental Industrial Hygienists, Lansing, Mich.
2. "Code of Federal Regulations Support M—Compressed Gas and Compressed Air Equipment," Section 1910.166, "Inspection of Compressed Gas Cylinders," *Federal Register,* Vol. 36, No. 105, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

15

Weldability and Properties of Metals

15-1 PROPERTIES OF METALS

When you look at a piece of bare metal it may appear brownish, it may look bright or dull, it might appear gray; it has color. One of the physical properties of a metal is its color. When you lift a piece of metal it may seem to be heavy or light. When you bend a thin piece of metal it may break or it may bend easily because it possesses ductility. If you attempt to melt the metal with a flame it may become liquid quickly or it may not melt. Metals have different melting temperatures.

These are some of the many different properties of metals which help describe and specify them. Metals have physical properties such as density, melting point, color, conductivity, and others. They also have mechanical properties, which include strength, hardness, ductility, and so on, and all of them can be tested. Many mechanical and physical properties of metals determine if and how they can be welded and how they will perform in service.

OUTLINE

Physical Properties

The physical properties of metals are given in both the metric system and the conventional system. In time, this will be standardized and we will all use the new SI terms which are based on international standards. Figure 15-1 shows the more common metals and their physical properties. Each is briefly described below.

Color Color relates to the quality of light reflected from the metal.

Mass Mass or density relates to mass with respect to volume. One of the more common ways of describing this property is by means of specific gravity, which is the ratio of the mass of a given volume of a metal to the mass of the same volume of water. This is at a specified temperature usually 39°F (4°C). The mass of a volume of water is taken as unity and the metals are related to it. In conventional terms this is taken as pounds per cubic foot of the metal or pounds per cubic inch. In the metric system this is taken as grams per cubic millimeter or centimeter.

Melting Point The melting point of a metal is extremely important with regard to welding. A metal's fusibility is related to its melting point, the temperature when the metal changes from a solid into a molten state. Mercury is the only common metal that is in its molten state at normal room temperature. Metals having low melting temperatures can be welded with lower temperature heat sources. The soldering and brazing processes utilize low-temperature metals to join metals having higher melting temperatures.

Boiling Point The boiling point is also an important factor in welding. The boiling point is the temperature at which the metal changes from the liquid state to vapor state. In welding, some metals, when exposed to the heat of an arc will vaporize.

Thermal Conductivity The thermal conductivity of a metal is its ability to transmit heat throughout its mass. It is of vital importance in welding since one metal may conduct or transmit heat from the welding area much more rapidly than another. It indicates the need for preheating and the size of heat source required. The thermal conductivity of metals is usually related to copper. Copper has the highest thermal conductivity of the common metals exceeded only by silver. Aluminum has approximately half the thermal conductivity of copper, and steels have only about one-tenth the conductivity of copper. Some data use silver as the standard and rate the thermal conductivity with respect to silver. Thermal conductivity is measured in calories per square centimeter per second per degree Celsius. However, since we are using a relative figure these are not used.

Specific Heat Specific heat is a measure of the quantity of heat required to increase the temperature of a metal by a specific amount. Specific heat is important in welding since it is an indication of the amount of heat required to bring the metal to its melting point. A metal having a low melting point but having a relatively high specific heat may require as much heat to bring it to its point of fusion as a metal of a high melting point and low specific heat. Specific heat is expressed in conventional as well as in metric forms. However, metric is more commonly used and it is the number of calories required to raise the temperature of 1 gram of metal 1 degree Celsius. It can be stated as a relative specific heat related to a standard. It is usually given at a standard temperature. Figure 15-1 provides the specific heat of the different metals based on the calories per gram per degrees C at 20° Celsius.

Expansion The coefficient of linear thermal expansion is a measure of the linear increase per unit length based on the change in temperature of the metal. Expansion is the increase in the dimension of a metal caused by heat. The expansion of a metal in a longitudinal direction is known as the linear expansion. The coefficient of linear expansion is expressed as the linear expansion per unit length for 1 degree of temperature rise.

The expansion of the metal in volume is called the volumetric expansion. Linear expansion is most commonly used and the data are available in both the conventional and metric values. The coefficient of linear expansion varies over a wide range for different metals. Aluminum has the greatest, expanding almost twice as much as steel for the same temperature change. This is important for welding with respect to warpage, warpage control and fixturing, and for welding dissimilar metals together.

Electrical Conductivity Electrical conductivity is the capacity of metal to conduct an electric current. A measure of electrical conductivity is provided by the conductance of a metal to the passage of electrical current. The reciprocal of conductivity is resistivity. Electrical resistivity is measured in micro-ohms per cubic centimeter at a standardized temperature, normally 20°C. Electrical conductivity, however, is usually considered as a percentage and is related to copper or silver. Temperature bears an important part in this property. As the temperature of a metal is increased, conductivity decreases. This property is particularly important to resistance welding and to electrical circuits.

Mechanical Properties

The mechanical properties of metals determine the range of usefulness of the metal and establish the service that can be expected. Mechanical properties are also used to help specify and identify metals. They are of vital interest to welding since the weld must provide mechanical properties in the same order as the base metals being joined. The adequacy of a weld depends on whether or not it pro-

FIGURE 15-1 **Physical properties of metals.**

Properties: Base Metal or Alloy	Specific Gravity	Density		Melting Point (Liquids)		Boiling Point[a]		Relative Thermal Conductivity Copper = 1	Co-efficient of Linear Expansion $\times 10^{-6}$ per Degree		Specific Heat Calories per Gram per °C	Electrical Conductivity in % Copper = 100%	Resistivity Microhms per Centimeter
		lb/ft³	g/cm³	°F	°C	°F	°C		°F	°C			
Aluminum and alloys	2.70	166	2.7	1218	659	3270	2480	0.52	13.8	24.8	0.22	59.0	2.8
Brass, navy	8.60	532	8.6	1650	900	NA	NA	0.28	11.8	21.2	0.09	28.0	6.6
Bronze, aluminum (90 Cu–9 Al)	7.69	480	7.7	1905	1040	NA	NA	0.15	16.6	29.9	0.014	12.8	13.5
Bronze, phosphor (90 Cu–10 Sn)	8.78	551	8.8	1830	1000	NA	NA	0.12	10.2	18.4	0.09	11.0	16.0
Bronze, silicon (96 Cu–3 Si)	8.72	542	8.7	1880	1025	NA	NA	0.10	10.0	18.0	0.09	7.0	NA
Copper (deoxidized)	8.89	556	8.9	1981	1081	4700	2600	1.00	9.8	17.6	0.095	100.0	1.7
Copper nickel (70 Cu–30 Ni)	8.81	557	8.8	2140	1172	NA	NA	0.07	9.0	16.2	0.09	4.6	37.0
Everdur (96 Cu–3 Si–1 Mn)	8.37	523	8.4	1866	1019	NA	NA	0.09	10.0	18.0	0.095	NA	NA
Gold	19.3	1205	19.3	1945	1061	5380	2950	0.76	7.8	14.0	0.032	71.0	2.2
Inconel (72 Ni–16 Cr–8 Fe)	8.25	530	8.3	2600	1425	NA	NA	0.04	6.4	11.5	0.109	1.5	98.1
Iron, cast	7.50	450	7.5	2300	1260	NA	NA	0.12	6.0	10.8	0.119	2.9	NA
Iron, wrought	7.80	485	7.8	2750	1510	5500	3000	0.16	6.7	12.1	0.115	15.0	NA
Lead	11.34	708	11.3	621	328	3100	1740	0.08	16.4	29.5	0.03	8.0	20.6
Magnesium	1.74	108	1.7	1202	650	2010	1100	0.40	14.3	25.7	0.246	37.0	5.0
Monel (67 Ni–30 Cu)	8.47	551	8.8	2400	1318	NA	NA	0.07	7.8	14.0	0.127	3.6	48.2
Nickel	8.8	556	8.8	2650	1452	5250	3000	0.16	7.4	13.3	0.105	23.0	7.9
Nickel silver	8.44	546	8.4	2030	1110	NA	NA	0.09	9.0	16.2	0.09	8.3	1.6
Silver	10.45	656	10.5	1764	962	4010	2210	1.07	10.6	19.1	0.056	106.0	—
Steel, low alloy	7.85	490	7.8	2600	1430	NA	NA	0.12	6.7	12.1	0.118	14.5	12.0
Steel, high carbon	7.85	490	7.8	2500	1374	NA	NA	0.17	6.7	12.1	0.118	9.5	18.0
Steel, low carbon	7.84	490	7.8	2700	1483	NA	NA	0.17	6.7	12.1	0.118	14.5	12.0
Steel, manganese (14 Mn)	7.81	490	7.8	2450	1342	NA	NA	0.04	6.7	12.1	0.210	NA	72.0
Steel, medium carbon	7.84	490	7.8	2600	1430	NA	NA	0.17	6.7	12.1	0.118	15.0	15.0
Steel, stainless (austentic)	7.9	495	7.9	2550	1395	NA	NA	0.12	9.6	17.3	0.117	3.0	75.0
Steel, stainless (matensitic)	7.7	485	7.7	2600	1430	NA	NA	0.17	9.5	17.1	0.118	3.0	57.0
Steel, stainless (ferritic)	7.7	485	7.7	2750	1507	NA	NA	0.17	9.5	17.1	0.334	3.0	60.0
Tantalum	16.6	1035	16.6	5162	2996	7410	5430	0.13	3.6	6.5	0.052	13.9	12.5
Tin	7.29	455	7.3	449	232	4100	2270	0.15	12.8	23.0	0.125	13.5	11.0
Titanium	4.5	281	4.5	3031	1668	5900	3200	0.04	4.0	7.2	0.113	1.1	42.0
Tungsten	18.8	1190	19.3	6170	3420	10600	5600	0.42	2.5	4.5	0.034	31.0	5.6
Zinc	7.13	442	7.1	788	419	1660	907	0.27	22.1	39.8	0.093	30.0	5.9

[a] NA, not available.

vides properties equal to or exceeding those of the metals being joined.

The most common properties of the common metals—strength, hardness, ductility, and impact resistance—are shown in Figure 15-2.

Strength The strength of a metal is its ability to withstand the action of external forces without breaking. *Tensile strength*, also called *ultimate strength*, is the maximum strength developed in a metal in a tension test. The tension test is a method for determining the behavior of a metal under an actual stretch loading. This test provides the elastic limit, elongation, yield point, yield strength, tensile strength, and the reduction in area. Tensile tests are normally taken at standardized room temperatures but may also be made at other temperatures. Figure 15-3 shows a tensile testing machine in operation. Many tensile testing machines are equipped to plot a curve which shows the load or stress and the strain or movement that occurs during the test operation. A typical curve for mild steel is shown in Figure 15-4. In the testing operation the load is increased gradually and the specimen will stretch or elongate in proportion to the tensile load. The specimen will elongate in direct proportion to the load during the elastic portion of the curve to point *A*. At this point, the specimen will continue to elongate but without an increase in the load. This is known as the yield point of the steel and is the end of the elastic portion. At any point up to point *A* if the load is eliminated, the specimen will come back to its original dimension. Yielding occurs from point *A* to point *B* and this is the area of plastic deformation. If the load were eliminated at point *B* the specimen would not go back to its original dimension but instead take a permanent *set*. Beyond point *B* the load will have to be increased to stretch the specimen further. The load will increase to point *C*, which is the ultimate strength of the material. At point *C* the specimen will break and the load is no longer carried. The ultimate tensile strength of the material is obtained by dividing the ultimate load by the cross-sectional area of

FIGURE 15-2 **Mechanical properties of metals.**

Properties:* Base Metal or Alloy	Yield Strength lb/in.^{2}	Yield Strength MPa	Yield Strength kg/mm^2	Tensile Strength lb/in.^{2}	Tensile Strength MPa	Tensile Strength kg/mm^2	Elongation % in 2 in. (50 mm)	Hardness (BHN)
Aluminum and alloys	5,000	34.5	3.5	13,000	89.6	9.1	35	23
Brass, navy	30,000	206.8	21.0	62,000	427.4	43.6	47	89
Bronze, alum. (90 Cu–9 Al)	30,000	206.8	21.0	76,000	523.9	53.4	10	125
Bronze, phosphor (90 Cu–10 Sn)	28,000	193.0	19.7	66,000	455.0	46.4	35	148
Bronze, silicon (96 Cu–3 Si)	15,000	103.4	10.5	40,000	275.8	28.1	52	119
Copper (deoxidized)	10,000	68.9	7.0	33,000	227.5	23.2	40	30
Copper nickel (70 Cu–30 Ni)	20,000	137.9	14.0	55,000	379.2	38.6	45	95
Everdur (96 Cu–3 Si–1 Mn)	20,000	137.9	14.0	55,000	379.2	38.6	60	75
Gold	—	—	—	17,000	117.2	11.9	45	25
Inconel (76 Ni–16 Cr–8 Fe)	35,000	241.3	24.6	85,000	586.0	59.7	45	150
Iron, cast	—	—	—	25,000	172.4	17.5	0.5	180
Iron, wrought	27,000	186.1	19.0	40,000	275.8	28.1	25	100
Lead	19,000	131.0	13.4	2,500	17.2	1.7	45	6
Magnesium	13,000	89.6	9.1	25,000	172.4	17.5	4	40
Monel (67 Ni–30 Cu)	35,000	241.3	24.6	75,000	517.1	52.7	45	125
Nickel	8,500	58.6	6.0	46,000	317.1	32.3	40	85
Nickel silver	20,000	137.9	14.0	58,000	399.8	40.7	35	90
Silver	8,000	55.2	5.6	23,000	158.6	16.2	35	90
Steel, low alloy	50,000	344.7	35.1	75,000	517.1	52.7	28	170
Steel, high carbon	90,000	620.5	63.2	140,000	965.2	98.4	20	201
Steel, low carbon	36,000	248.2	25.3	60,000	413.6	42.2	35	310
Steel, manganese (14 Mn)	75,000	517.1	52.7	118,000	813.5	82.9	22	200
Steel, medium carbon	52,000	358.5	36.5	87,000	599.8	61.2	24	170
Steel, stainless (austentic)	40,000	275.8	28.1	90,000	620.5	63.2	23	160
Steel, stainless (matensitic)	80,000	551.5	56.2	100,000	68.9	70.3	26	250
Steel, stainless (ferritic)	45,000	310.2	31.6	75,000	517.1	52.7	30	155
Tantalum	—	—	—	50,000	344.7	35.1	40	300
Tin	1,710	11.8	1.2	3,130	21.6	2.2	50	5.3
Titanium	40,000	275.8	28.1	60,000	413.6	42.2	28	—
Tungsten	—	—	—	500,000	3447.0	351.5	15	230
Zinc	18,000	124.1	12.6	25,000	172.35	17.5	20	38

*Values depend on heat treatment or mechanical condition or mass of the metal.

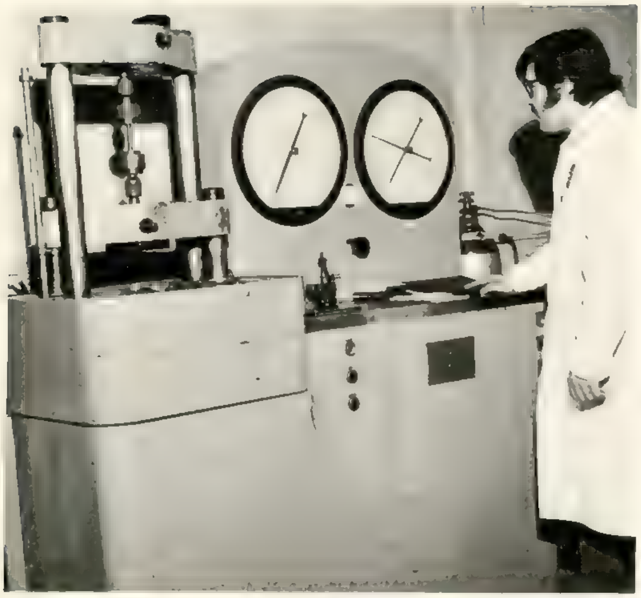
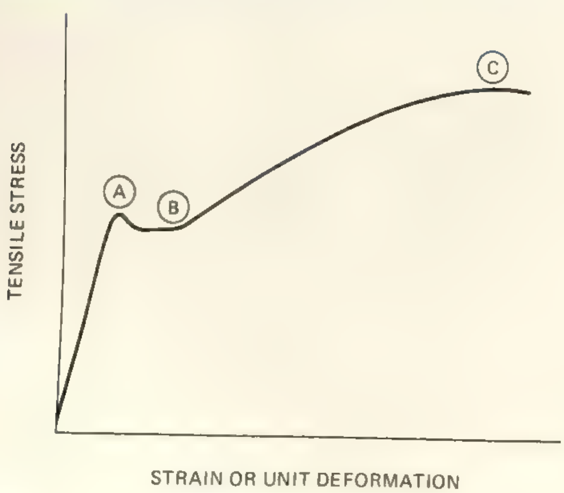


FIGURE 15-3 Tensile test machine.

the original specimen. This provides the ultimate tensile strength in pounds per square inch or kilograms per square millimeter.

The *yield stress* or *yield point* is obtained by dividing the load at yield or at point *A* by the original area. This provides a figure in pounds per square inch or kilograms per square millimeter. Extremely ductile metals do not have a yield point. They stretch or yield at low loads. For these metals the yield point is determined by the change in elongation. Two tenths of one percent elongation is arbitrarily set as the yield point. The yield point is the limit upon which designs are calculated. Designs of weldments are expected to perform within the elastic limit and the yield point is the measure of that limit.

FIGURE 15-4 Stress-strain curve.



Ductility The ductility of a metal is the property that allows it to be stretched or otherwise changed in shape without breaking and to retain the changed shape after the load has been removed. The ductility of a metal can be determined from the tensile test. This is done by determining the percent of elongation. Gauge marks are made 2 in. apart across the point where fracture will occur. The increase in gauge length related to the original length times 100 is the percentage of elongation. This is done by making center punch marks 2 in. apart at the reduced section of the test coupon, testing the coupon, tightly holding the two pieces together and remeasuring the distance between the center punch marks. The original 2 in. is subtracted from the measured length and the difference is divided by 2 and multiplied by 100 to obtain percentage of elongation.

Ductility of welds or of metals can also be measured by the bend test. In this case, gauge lines are drawn before testing, measured, and measured again after bending. The difference divided by the original length times 100 is the elongation in percentage.

The ductility is of extreme interest to welding since a higher ductility indicates a weld which would be less likely to crack in service. Figure 15-5 shows typical tensile specimens: unbroken, ductile, and brittle fracture.

Reduction of Area Reduction of area is another measure of ductility and is obtained from the tensile test by measuring the original cross-sectional area of the specimen and relating it to the cross-sectional area after failure. For a round specimen the diameter is measured and the cross-sectional area is calculated. After the test bar is broken the diameter is measured at the smallest point. The cross-sectional area is again calculated. The difference in area is divided by the original area and multiplied by 100 to give the percentage reduction of area. This figure is of less importance than the elongation but is usually reported when the mechanical properties of a metal are given.

FIGURE 15-5 Tensile specimens.

The tensile test specimen also provides another property of metal known as its modulus of elasticity, also called *Young's modulus*. This is the ratio of the stress to the elastic strain. It relates to the slope of the curve to the yield point. For iron or steel the modulus of elasticity is approximately 30,000,000 psi, for aluminum it is approximately 10,300,000 psi, for copper 15,000,000 psi, and for magnesium 6,500,000 psi. The modulus of elasticity is important to designers and is incorporated in many design formulas.

Hardness The hardness of a metal is defined as the resistance of a metal to local penetration by harder substance. The hardness of metals is measured by forcing a hardened steel ball or diamond into the surface of the specimen, under a definite weight, in a hardness testing machine. Figure 15-6 shows the Vickers hardness testing machine. The Brinell is one of the more popular types of machines for measuring hardness. It provides a Brinell hardness number (BHN), which is in kilograms per square millimeter based on the load applied to the hardened ball in kilograms and divided by the area of the impression left by the ball in square millimeters. These metric factors are disregarded and hardness is measured strictly as a Brinell hardness number. The BHN is obtained by an optical magnifier which reads the diameter of the impression and produces a hardness number. Various scales are used in the Brinell hardness testing system based on the load and the diameter of the ball, usually 10 mm using a 3000-kg load.

There are several other hardness measuring systems. A popular machine is the Rockwell hardness tester (Figure 15-7), which utilizes a diamond which is forced into the surface of the specimen. Different loads are used to provide different scales. Smaller loads are used for softer materials. The optical unit is not required since the hardness is read from a dial mounted on the machine which relates to the penetration. There is also the superficial Rockwell hardness tester for measuring surface hardnesses of metals. Another method is by means of the Vickers hardness machine, which reads directly, as a diamond is pressed into the surface of the metal. Another way is the Shore scleroscope, which utilizes a small dropped weight which will bounce from the surface of the metal, providing a hardness measure. This device is used for field work and is not considered as accurate as those that make impressions. Figure 15-8 shows the hardness conversion numbers for these different hardness measuring systems. It is also possible to relate the approximate strength of a metal to its hardness as shown in the figure. Portable electronic units are now available for field use.

Impact Resistance Resistance of a metal to impacts is evaluated in terms of impact strength. A metal may possess satisfactory ductility under static loads but may

FIGURE 15-6 Vickers hardness testing machine.

FIGURE 15-7 Rockwell hardness testing machine.

Brinell		Vickers or Firth Hardness No.	Rockwell		Scleroscope No.	Approximate Tensile Strength, 1000 psi
			C	B		
Dia. (mm); 3000-kg Load, 10-mm Ball	Hardness No.		150-kg Load 120° Diamond Cone	100-kg Load 1/16-in.-dia. Ball		
2.05	898					440
2.10	857					420
2.15	817					401
2.20	780	1150	70		106	384
2.25	745	1050	68		100	368
2.30	712	960	66		95	352
2.35	682	885	64		91	337
2.40	653	820	62		87	324
2.45	627	765	60		84	311
2.50	601	717	58		81	298
2.55	578	675	57		78	287
2.60	555	633	55	120	75	276
2.65	534	598	53	119	72	266
2.70	514	567	52	119	70	256
2.75	495	540	50	117	67	247
2.80	477	515	49	117	65	238
2.85	461	494	47	116	63	229
2.90	444	472	46	115	61	220
2.95	429	454	45	115	59	212
3.00	415	437	44	114	57	204
3.05	401	420	42	113	55	196
3.10	388	404	41	112	54	189
3.15	375	389	40	112	52	182
3.20	363	375	38	110	51	176
3.25	352	363	37	110	49	170
3.30	341	350	36	109	48	165
3.35	331	339	35	109	46	160
3.40	321	327	34	108	45	155
3.45	311	316	33	108	44	150
3.50	302	305	32	107	43	146
3.55	293	296	31	106	42	142
3.60	285	287	30	105	40	138
3.65	277	279	29	104	39	134
3.70	269	270	28	104	38	131
3.75	262	263	26	103	37	128
3.80	255	256	25	102	37	125
3.85	248	248	24	102	36	122
3.90	241	241	23	100	35	119
3.95	235	235	22	99	34	116
4.00	229	229	21	98	33	113
4.05	223	223	20	97	32	110
4.10	217	217	18	96	31	107
4.15	212	212	17	96	31	104
4.20	207	207	16	95	30	101
4.25	202	202	15	94	30	99
4.30	197	197	13	93	29	97
4.35	192	192	12	92	28	95
4.40	187	187	10	91	28	93
4.45	183	183	9	90	27	91
4.50	179	179	8	89	27	89
4.55	174	174	7	88	26	87
4.60	170	170	6	87	26	85
4.65	166	166	4	86	25	83
4.70	163	163	3	85	25	82
4.75	159	159	2	84	24	80
4.80	156	156	1	83	24	78
4.85	153	153		82	23	76
4.90	149	149		81	23	75

FIGURE 15-8 Hardness conversion table.

Brinell			Rockwell			
Dia. (mm); 3000-kg Load, 10-mm Ball	Hardness No.	Vickers or Firth Hardness No.	C 150-kg Load 120° Diamond Cone	B 100-kg Load 1/16-in.-dia. Ball	Scleroscope No.	Approximate Tensile Strength, 1000 psi
4.95	146	146		80	22	74
5.00	143	143		79	22	72
5.05	140	140		78	21	71
5.10	137	137		77	21	70
5.15	134	134		76	21	68
5.20	131	131		74	20	66
5.25	128	128		73	20	65
5.30	126	126		72		64
5.35	124	124		71		63
5.40	121	121		70		62
5.45	118	118		69		61
5.50	116	116		68		60
5.55	114	114		67		59
5.60	112	112		66		58
5.65	109	109		65		56
5.70	107	107		64		56
5.75	105	105		62		54
5.80	103	103		61		53
5.85	101	101		60		52
5.90	99	99		59		51
5.95	97	97		57		50
6.00	95	95		56		49

Note. Hardness conversion tables are approximate.

FIGURE 15-8 (*cont.*)

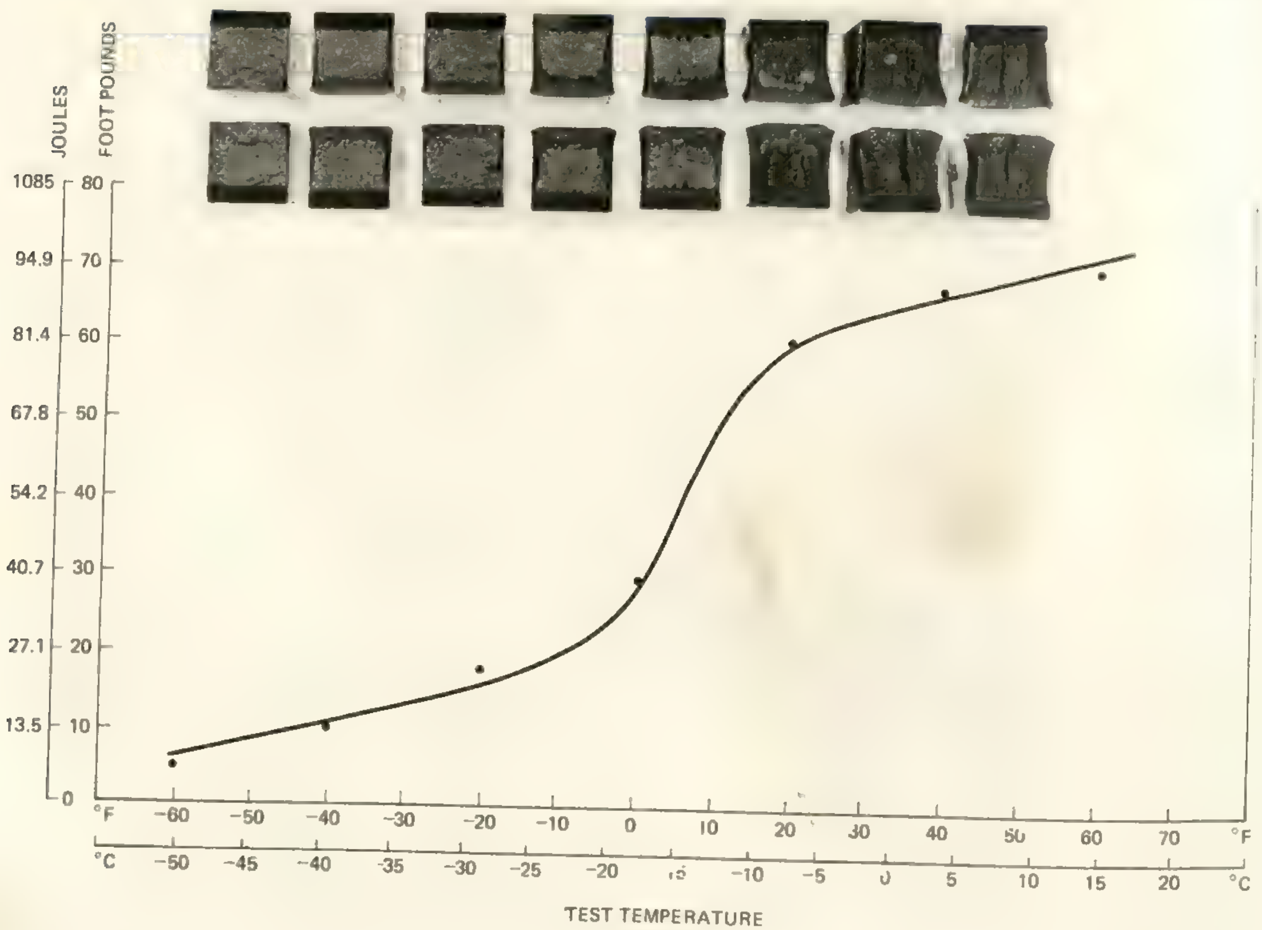
fail under dynamic loads or impact. Impact strength is most often determined by the Charpy test. It is sometimes measured by the Izode test. Both types of tests use the same type of pendulum-testing machine. The Charpy test specimen is a beam supported at both ends and contains a notch in the center. The specimen is placed on supports and struck with a pendulum on the side opposite the notch. The accuracy and location of the notch is of extreme importance. There are several types of Charpy specimens; the V-notch type is the most popular. The specimen is standardized in metric dimensions. Figure 15-9 shows the impact testing machine in action.

The impact strength of a metal is determined by measuring the energy absorbed in the fracture. This is equal to the weight of the pendulum times the height at which the pendulum is released and the height to which the pendulum swings afteer it has struck the specimen. In conventional terms the impact strength is the foot pounds of energy absorbed. In metric practice, impact resistance is measured two ways: (1) the kilogram-meter based on energy absorbed and (2) the kilogram-meter per square centimeter of the area of the fractured surface or the cross-sectional area under the notch. Both terms are used, but care must be taken to determine which is appropriate. The SI system measures energy absorbed in joules. Figure 15-10 shows V-notch Charpy impact bars before and after testing.

FIGURE 15-9 Making an impact test.

FIGURE 15-10 V-notch Charpy impact bars.

FIGURE 15-11 Transition chart of impact tests.



Impact tests are often made at different temperatures, since steels normally become more brittle or will absorb less energy at lower temperatures. Normally, seven specimens are broken at each test temperature and the high and low values are discarded. The reported value is the average of the remaining two specimens. Test temperatures are −60 °F (−51 °C), −50 °F (−46 °C), −40 °F (−40 °C), −20 °F (−29 °C), −14 °F (−25 °C), −4 °F (−20 °C), 0 °F (−18 °C), 14 °F (−10 °C), 32 °F (0 °C), 50 °F (10 °C), 68 °F (20 °C). All temperatures may not be used; however, usually five test temperatures are used so that a transition curve can be drawn. Figure 15-11 shows a temperature transition curve. At the point of *fall-off* the transition changes from ductile to brittle. This is known as the *transition temperature*. The change from ductile to brittle fracture can also be seen by the surface of the broken bars in the figure. Another measure of ductility is also utilized and this is the degree of lateral expansion of the bar at the fracture surface. The greater the degree of change, the more ductile the fracture. The fracture surface type is also reported for critical requirements. All these different tests and test specimens are standardized by the American Society for Testing and Materials.

15-2 METAL SPECIFICATIONS AND STEEL CLASSIFICATION

There are many different ways that metals are identified and specified. These range from national specifications, professional society specifications, trade association specifications, to trade names of specific metals. In North America, the most popular method of specifying a metal is by its ASTM number. ASTM stands for the American Society for Testing and Materials, which issues an annual book of standards consisting of at least 33 parts. Seven parts specify metals:

- *Part 1:* steel piping, tubing, and fittings
- *Part 2:* ferrous castings–ferroalloys
- *Part 3:* steel sheet, strip, bar, rod, wire, etc.
- *Part 4:* structural steel, steel plate, steel rails, wheels, etc.
- *Part 5:* copper and copper alloys
- *Part 6:* die-cast metals, light metals, and alloys
- *Part 7:* nonferrous metals and alloys, etc.

Other sections cover basic materials such as concrete, chemicals, insulating materials, papers, petroleum products, fuels, paint, textiles, plastics, and rubber.

ASTM issues three parts that relate to testing;

- *Part 30:* General test methods
- *Part 31:* Metals—physical and mechanical nondestructive tests
- *Part 32:* Analytical methods of analysis

The ASTM standards represent a consensus viewpoint of parties concerned with its provisions: producers, users, and general interest groups. These are voluntary standards written by committees of the membership. The ASTM standards for metals provide the mechanical properties of the metal and in many cases chemical composition. Specifications for steels usually provide compositions that refer to either the analysis of the steel in the ladle or in its final form. The specifications also provide information concerning the form and size of the products, the size tolerance of products, testing procedures, inspection information, and so on.

The ASTM metal specifications are identified by a prefix letter, A indicating ferrous materials and B indicating nonferrous metals. This is followed by a one-, two-, or three-digit number indicating the exact specification number, which is then followed by a two-digit number indicating the year that the specification was formally adopted. A suffix letter T, when used, indicates that it is a tentative specification.

There are too many ASTM specifications to be listed here and it is therefore recommended that the first seven parts or volumes be examined for a better understanding of the usefulness of the ASTM specifications.

Each part or volume is updated periodically and is available from the society. Many libraries have the ASTM volumes. Individual standards are available from the society.

The term *steel* encompasses many types of metals made principally of iron. Steel is an alloy of iron and carbon, but steels most often contain other metals such as manganese, chromium, and nickel, and nonmetals such as carbon, silicon, phosphorus, sulfur, and others. It is necessary to consider the different steels—how they are classified and identified.

There are so many different types and kinds of steels that it is sometimes confusing just to be able to identify the steel that is being used. For example, there are structural steels, cast steels, stainless steels, tool steels, hot rolled steel, reinforcing steel, low-alloy high-strength steel, and so on. Steels are sometimes given names based on their principal alloy, such as carbon steel, chrome-manganese steel, chrome-moly steel, and so on. Sometimes steels are identified by numbers, such as C-1020 steel, A36 steel, SAE 1045 steel, type 304 steel, and so on. In other cases, steels may be identified by letters, such as AR steels, T-1 steels, RQC steels, NAX steels, and so on. Steels are also called by a trade name given by their manufacturer. Examples of this are Mayari steel, Corten steel, Jalloy steel, and Naxtra steel. All these names tend to add to the confusion, but they are clues for finding the true identification of a steel.

The method of the manufacture of the steel also enters into the identification system. This would include cast steel, hot- or cold-rolled steels, forged steels, semi-killed steels, and continuous cast steel.

The two best ways of identifying a steel are by its specification number and grade or trade name and number. In the case of the specification, it should be consulted to determine composition and properties, and it is necessary to determine the sponsoring group of the specification. When a trade name is used, the manufacturer's literature should be consulted for composition and properties. Of course, it is necessary to determine the manufacturer. When this is known, the identity of the steel can be determined.

A popular system for classifying steels is the American Iron and Steel Institute Numerical Designation of Standard Carbon and Alloy Steels.[1] This is known as the AISI designation system and sometimes known as the SAE system since it was originated by the Society of Automotive Engineers. The groupings of steels within this numerical system are shown in Figure 15-12. Numbers are used to designate different chemical compositions.

FIGURE 15-12 AISI-SAE numerical designation of carbon and alloy steels.

SAE Steel Specifications

The following numerical system for identifying carbon and alloy steels of various specifications has been adopted by the Society of Automotive Engineers.

COMPARISON

AISI–SAE Steel Specifications

The ever-growing variety of chemical compositions and quality requirements of steel specifications have resulted in several thousand different combinations of chemical elements being specified to meet individual demands of purchasers of steel products.

The SAE developed an excellent system of nomenclature for identification of various chemical compositions which have symbolized certain standards as to machining, heat treating, and carburizing performance. The American Iron and Steel Institute has now gone further in this regard with a new standardization setup with similar nomenclature but with restricted carbon ranges and combinations of other elements which have been accepted as standard by all manufacturers of bar steel in the steel industry, because it has become apparent that steel producers must concentrate their efforts on a smaller number of standardized grades. The Society of Automotive Engineers have as a result revised most of their specifications to coincide with those set up by the American Iron and Steel Institute.

PREFIX LETTERS—

No prefix for basic open-hearth alloy steel.
(B) Indicates acid Bessemer carbon steel.
(C) Indicates basic open-hearth carbon steel.
(E) Indicates electric furnace steel.

NUMBER DESIGNATIONS—

(10XX series)	Basic open-hearth and acid Bessemer carbon steel grades, nonsulfurized and nonphosphorized.
(11XX series)	Basic open-hearth and acid Bessemer carbon steel grades, sulfurized but not phosphorized.
(1300 series)	Manganese 1.60 to 1.90%
(23XX series)	Nickel 3.50%
(25XX series)	Nickel 5.0%
(31XX series)	Nickel 1.25%–Chromium .60%
(33XX series)	(Nickel 3.50%–Chromium 1.60%
(40XX series)	Molybdenum
(41XX series)	Chromium–Molybdenum
(43XX series)	Nickel–chromium–molybdenum
(46XX series)	(Nickel 1.65%–molybdenum 0.25%
(48XX series)	Nickel 3.25%–molybdenum 0.25%
(51XX series)	Chromium
(52XX series)	Chromium and high carbon
(61XX series)	Chromium–vanadium
(86XX series)	Chrome–nickel–molybdenum
(87XX series)	Chrome–nickel–molybdenum
(92XX series)	Silicon 2.0%–chromium
(93XX series)	Nickel 3.0%–chromium–molybdenum
(94XX series)	Nickel–chromium–molybdenum
(97XX series)	Nickel–chromium–molybdenum
(98XX series)	Nickel–chromium–molybdenum

Carbon Steels

SAE Number	C	Mn	P Max.	S Max.	AISI Number
—	0.06 max.	0.35 max.	0.040	0.050	C1005
1006	0.08 max.	0.25–0.40	0.040	0.050	C1006
1008	0.10 max.	0.25–0.50	0.040	0.050	C1008
1010	0.08–0.13	0.30–0.60	0.040	0.050	C1010
—	0.10–0.15	0.30–0.60	0.040	0.050	C1012
—	0.11–0.16	0.50–0.80	0.040	0.050	C1013
1015	0.13–0.18	0.30–0.60	0.040	0.050	C1015
1016	0.13–0.18	0.60–0.90	0.040	0.050	C1016
1017	0.15–0.20	0.30–0.60	0.040	0.050	C1017
1018	0.15–0.20	0.60–0.90	0.040	0.050	C1018
1019	0.15–0.20	0.70–1.00	0.040	0.050	C1019
1020	0.18–0.23	0.30–0.60	0.040	0.050	C1020
—	0.18–0.23	0.60–0.90	0.040	0.050	C1021
1022	0.18–0.23	0.70–1.00	0.040	0.050	C1022
—	0.20–0.25	0.30–0.60	0.040	0.050	C1023
1024	0.19–0.25	1.35–1.65	0.040	0.050	C1024
1025	0.22–0.28	0.30–0.60	0.040	0.050	C1025
—	0.22–0.28	0.60–0.90	0.040	0.050	C1026
1027	0.22–0.29	1.20–1.50	0.040	0.050	C1027
—	0.25–0.31	0.60–0.90	0.040	0.050	C1029
1030	0.28–0.34	0.60–0.90	0.040	0.050	C1030
1033	0.30–0.36	0.79–1.00	0.040	0.050	C1033
1034	0.32–0.38	0.50–0.80	0.040	0.050	C1034
1035	0.32–0.38	0.60–0.90	0.040	0.050	C1035
1036	0.30–0.37	1.20–1.50	0.040	0.050	C1036
1038	0.35–0.42	0.60–0.90	0.040	0.050	C1038
—	0.37–0.44	0.70–1.00	0.040	0.050	C1039
1040	0.37–0.44	0.60–0.90	0.040	0.050	C1040
1041	0.36–0.44	1.35–1.65	0.040	0.050	C1041
1042	0.40–0.47	0.60–0.90	0.040	0.050	C1042
1043	0.40–0.47	0.70–1.00	0.040	0.050	C1043
1045	0.43–0.50	0.60–0.90	0.040	0.050	C1045
1046	0.43–0.50	0.70–1.00	0.040	0.050	C1046
1050	0.48–0.55	0.60–0.90	0.040	0.050	C1050
—	0.45–0.56	0.85–1.15	0.040	0.050	C1051
1052	0.47–0.55	1.20–1.50	0.040	0.050	C1052
—	0.50–0.60	0.50–0.80	0.040	0.050	C1054
1055	0.50–0.60	0.60–0.90	0.040	0.050	C1055
—	0.50–0.61	0.85–1.15	0.040	0.050	C1057
—	0.55–0.65	0.50–0.80	0.040	0.050	C1059
1060	0.55–0.65	0.60–0.90	0.040	0.050	C1060
—	0.54–0.65	0.75–1.05	0.040	0.050	C1061
1062	0.54–0.65	0.85–1.15	0.040	0.050	C1062
1064	0.60–0.70	0.50–0.80	0.040	0.050	C1064
1065	0.60–0.70	0.60–0.90	0.040	0.050	C1065
1066	0.60–0.71	0.85–1.15	0.040	0.050	C1066
—	0.65–0.75	0.40–0.70	0.040	0.050	C1069
1070	0.65–0.75	0.60–0.90	0.040	0.050	C1070
—	0.65–0.76	0.75–1.05	0.040	0.050	C1071
1074	0.70–0.80	0.50–0.80	0.040	0.050	C1074

Alloy Steel

AISI Number	C	Mn	P Max.	S Max.	Si	Ni	Cr	Other	SAE Number
1320	0.18–0.23	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—	1320
1321	0.17–0.22	1.80–2.10	0.050	0.050	0.20–0.35	—	—	—	—
1330	0.28–0.33	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—	1330
1335	0.33–0.38	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—	1335
1340	0.38–0.43	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—	1340
2317	0.15–0.20	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	—	2317

Alloy Steel (*cont.*)

AISI Number	C	Mn	P Max.	S Max.	Si	Ni	Cr	Other	SAE Number
2330	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	3.25–3.75	—	—	2330
2335	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	3.25–3.75	—	—	—
2340	0.33–0.43	0.70–0.90	0.040	0.040	0.20–0.35	3.25–3.75	—	—	2340
2345	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	3.25–3.75	—	—	2345
E2512	0.09–0.14	0.45–0.60	0.025	0.025	0.20–0.35	4.75–5.25	—	—	2512
2515	0.12–0.17	0.40–0.60	0.040	0.040	0.20–0.35	4.75–5.25	—	—	2515
E2517	0.15–0.20	0.45–0.60	0.025	0.025	0.20–0.35	4.75–5.25	—	—	2517
3115	0.13–0.18	0.40–0.60	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—	3115
3120	0.17–0.22	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—	3120
3130	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—	3130
3135	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—	3135
3140	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—	3140
3141	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	—	3141
3145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	—	3145
3150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	—	3150
E3310	0.08–0.13	0.45–0.60	0.025	0.025	0.20–0.35	3.25–3.75	1.40–1.75	—	3310
E3316	0.14–0.19	0.45–0.60	0.025	0.025	0.20–0.35	3.25–3.75	1.40–1.75	—	3316
								Mo	
4017	0.15–0.20	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4017
4023	0.20–0.25	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4023
4024	0.20–0.25	0.70–0.90	0.040	0.035–0.050	0.20–0.35	—	—	0.20–0.30	4024
4027	0.25–0.30	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4027
4028	0.25–0.30	0.70–0.90	0.040	0.035–0.050	0.20–0.35	—	—	0.20–0.30	4028
4032	0.30–0.35	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4032
4037	0.35–0.40	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4037
4042	0.40–0.45	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4042
4047	0.45–0.50	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4047
4053	0.50–0.56	0.75–1.00	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4053
4063	0.60–0.67	0.75–1.00	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4063
4068	0.63–0.70	0.75–1.00	0.040	0.040	0.20–0.35	—	—	0.20–0.30	4068
—	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	—	0.40–0.60	0.20–0.30	4119
—	0.23–0.28	0.70–0.90	0.040	0.040	0.20–0.35	—	0.40–0.60	0.20–0.30	4125
4130	0.28–0.33	0.40–0.60	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25	4130
E4132	0.30–0.35	0.40–0.60	0.025	0.025	0.20–0.35	—	0.80–1.10	0.18–0.25	—
E4135	0.33–0.38	0.70–0.90	0.025	0.025	0.20–0.35	—	0.80–1.10	0.18–0.25	—
4137	0.35–0.40	0.70–0.90	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25	4137
E4137	0.35–0.40	0.70–0.90	0.025	0.025	0.20–0.35	—	0.80–1.10	0.18–0.25	—
4140	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.18–0.25	4140
4142	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25	—
4145	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25	4145
4147	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25	—
4150	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25	4150
4317	0.15–0.20	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	0.40–0.60	0.20–0.30	4317
4320	0.17–0.22	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	0.40–0.60	0.20–0.30	4320
4337	0.35–0.40	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30	—
4340	0.38–0.43	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30	4340
4608	0.06–0.11	0.25–0.45	0.040	0.040	0.25 Max	1.40–1.75	—	0.15–0.25	4608
4615	0.13–0.18	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30	4615
—	0.15–0.20	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30	4617
E4617	0.15–0.20	0.45–0.65	0.025	0.025	0.20–0.35	1.65–2.00	—	0.20–0.27	—
4620	0.17–0.22	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30	4620
X4620	0.18–0.23	0.50–0.70	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30	X4620
E4620	0.17–0.22	0.45–0.65	0.025	0.025	0.20–0.35	1.65–2.00	—	0.20–0.27	—
4621	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30	4621
4640	0.38–0.43	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30	4640
E4640	0.38–0.43	0.60–0.80	0.025	0.025	0.20–0.35	1.65–2.00	—	0.20–0.27	—
4812	0.10–0.15	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30	4812
4815	0.13–0.18	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30	4815
4817	0.15–0.20	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30	4817
4820	0.18–0.23	0.50–0.70	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30	4820

Alloy Steel (*cont.*)

AISI Number	C	Mn	P Max.	S Max.	Si	Ni	Cr	Other	SAE Number
5045	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	–	0.55–0.75	–	5045
5046	0.43–0.50	0.75–1.00	0.040	0.040	0.20–0.35	–	0.20–0.35	–	5046
–	0.13–0.18	0.70–0.90	0.040	0.040	0.20–0.35	–	0.70–0.90	–	5115
5120	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	–	0.70–0.90	–	5120
5130	0.28–0.33	0.70–0.90	0.040	0.040	0.20–0.35	–	0.80–1.10	–	5130
5132	0.30–0.35	0.60–0.80	0.040	0.040	0.20–0.35	–	0.80–1.05	–	5132
5135	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	–	0.80–1.05	–	5135
5140	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	–	0.70–0.90	–	5140
5145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	–	0.70–0.90	–	5145
5147	0.45–0.52	0.75–1.00	0.040	0.040	0.20–0.35	–	0.90–1.20	–	5147
5150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	–	0.70–0.90	–	5150
5152	0.48–0.55	0.70–0.90	0.040	0.040	0.20–0.35	–	0.90–1.20	–	5152
E50100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	–	0.40–0.60	–	50100
E51100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	–	0.90–1.15	–	51100
E52100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	–	1.30–1.60	–	52100
								V	
6120	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	–	0.70–0.90	0.10 Min	–
6145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	–	0.80–1.10	0.15 Min	–
6150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	–	0.80–1.10	0.15 Min	6150
6152	0.48–0.55	0.70–0.90	0.040	0.040	0.20–0.35	–	0.80–1.10	0.10 Min	–
								Mo	
8615	0.13–0.18	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.50–0.60	0.15–0.25	8615
8617	0.15–0.20	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8617
8620	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8620
8622	0.20–0.25	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8622
8625	0.23–0.28	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8625
8627	0.25–0.30	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8627
8630	0.28–0.33	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8630
8632	0.30–0.35	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8632
8635	0.33–0.38	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8635
8637	0.35–0.40	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8637
8640	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8640
8641	0.38–0.43	0.75–1.00	0.040	0.040–0.060	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8641
8642	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8642
8645	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8645
8647	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8647
8650	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8650
8653	0.50–0.56	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8653
8655	0.50–0.60	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8655
8660	0.50–0.65	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8660
8720	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8720
8735	0.33–0.38	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8735
8740	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8740
8742	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	–
8745	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8745
8747	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	–
8750	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8750
–	0.50–0.60	0.50–0.60	0.040	0.040	1.20–1.60	–	0.50–0.80	–	9254
9255	0.50–0.60	0.70–0.95	0.040	0.040	1.80–2.20	–	–	–	9255
9260	0.55–0.65	0.70–1.00	0.040	0.040	1.80–2.20	–	–	–	9260
9261	0.55–0.65	0.75–1.00	0.040	0.040	1.80–2.20	–	0.10–0.25	–	9261
9262	0.55–0.65	0.75–1.00	0.040	0.040	1.80–2.20	–	0.25–0.40	–	9262
E9310	0.08–0.13	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15	9310
E9315	0.13–0.18	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15	9315
E9317	0.15–0.20	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15	9317
9437	0.35–0.40	0.90–1.20	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9437
9440	0.38–0.43	0.90–1.20	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9440
9442	0.40–0.45	1.00–1.30	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9442
9445	0.43–0.48	1.00–1.30	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9445
9747	0.45–0.50	0.50–0.80	0.040	0.040	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25	9747

Alloy Steel (*cont.*)

AISI Number	C	Mn	P Max.	S Max.	Si	Ni	Cr	Other	SAE Number
9763	0.60–0.67	0.50–0.80	0.040	0.040	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25	9763
9840	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30	9840
9845	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30	9845
9850	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30	9850

A four-digit number series designates carbon and alloy steels according to the types and classes. This system has been expanded and in some cases five digits are used to designate certain alloy steels. The last two digits are intended to indicate the approximate middle of the carbon range; for example, 0.21 indicates a range of 0.18 to 0.23% carbon. In a few cases, the system deviates from this rule and some carbon ranges relate to the ranges of manganese, sulfur, phosphorus, chromium, and other elements. Two letters are often used as a prefix to the numerals. The letter C indicates basic open hearth carbon steel, and E indicates electric furnace carbon and alloy steels. The letter H is sometimes used as a suffix to denote steels manufactured to meet hardenability limits. The first two digits indicate the major alloying metals in the steel such as manganese, nickel–chromium, chrome–molybdenum, and so on.

Other organizations that specify steels include the American Petroleum Institute (API), the American Association of Railroads (AAR), the American Bureau of Shipping (ABS), the Steel Founders Society of America (SFSA), the Society of Automotive Engineers (SAE), which include the AMS specifications as well as many government agencies and private companies. In view of this, it is necessary to learn the different specifying groups and obtain copies of specifications or literature concerning the steels that are to be welded.

The AISI and SAE also collaborated on a system of identifying the corrosion-resistant or stainless steels. In this system stainless and heat-resistant steels are classified into four general groups. They are identified by a three-digit number. The first number indicates the group and the last two numbers indicate the type. Modifications of types are indicated by suffix numbers. Information concerning the exact specifications for different steels will be given in Section 16-3.

Different branches of the U.S. federal government also write specifications for metals. The Department of Defense issues the MIL specifications and the Department of Commerce issues the QQ specifications. Other groups may also issue metal specifications.

Professional societies and trade associations provide specifications for metals. For example, the American Petroleum Institute issues specifications covering the mechanical properties and composition of steel for pipe. The American Bureau of Shipping provides specifications for steels used in shipbuilding. The Association for American Railroads provides specifications for wrought and cast steels used by the railroad industry.

Steel castings are identified and specified by ASTM specifications and also by SAE, AAR, and ABS classes. These specifications provide for mechanical properties with various heat treatments and chemical compositions.

Specifications for materials used in the aircraft industry are designated as AMS, which stands for Aerospace Materials Specifications, which is a division of the Society of Automotive Engineers (SAE).

Most industrialized countries have national standards which provide specifications for metals. The British Standards (BS) issue specifications for many different types of metals, as do the German Standardization Institute (DIN) and the Japanese Standards Association (JIS). The standardization department of the Soviet Union issues GOST standards. Most of these standards are available in their original language from the standardization society of the countries. The International Organization of Standards (ISO) also issues specifications for metals.

For nonferrous metals several trade associations are involved. For example, the Aluminum Association provides a system of designating the compositions of aluminum alloys. This system uses four-digit numbers for wrought aluminum alloys. The AA also provides temper designations as suffix letters and numbers to indicate the temper condition. All of the aluminum producers in North America utilize the Aluminum Association alloy numbers for identifying their different products. More information is given in Section 17-1.

A standard designation for copper and copper alloys has been established by the Copper Development Association, Inc. Their system is used in North America and has been adopted by the U.S. government, ASTM, SAE, and nearly all producers of copper and copper alloy products. It is not a specification but rather an orderly method using a three-digit number of defining and identifying coppers and copper alloys. The system groups compositions into families, including the coppers, the high-copper alloys, the brasses, the bronzes, the copper–nickels, and the copper–zinc alloys. These numbers replace previous trade names such as copper–nickel, aluminum–bronze, phosphur–bronze, Naval-brass, tough pitch copper, etc.

The alloys of magnesium are identified by a special designation established by ASTM. Titanium, lead, tin, and other metals are specified by ASTM specifications. Specifications applicable to each metal will be provided in the chapter concerning each metal.

There are, numerous alloys that are identified by trade names or numbers by the producer. Compositions of these alloys can be obtained from the producer. The Society of Automotive Engineers (SAE) also provides specifications for nonferrous metals.

Several books are available[1–4] that list different alloys and metals by trade name. For those who need to determine the analysis of different proprietory or trade name alloys, these books are of immense value.

15-3 IDENTIFICATION OF METALS

Often, particularly in repair work, it is necessary to weld on a material whose specification or trade name or composition is unknown. To produce a successful weld, it is necessary to know the composition of the metal being welded. There are a number of ways to determine the composition so that a welding procedure can be developed. The ability to make a rapid identification of the metal will reduce the time required to make a successful weld. If time permits, it is recommended that a piece of the metal be taken to a laboratory for analysis. Since time is rarely available, the following basis for identifying the metal should be followed. By using this technique and with experience a fairly accurate identification can be made.

There are seven simple tests that can be performed to help identify metals. They will at least provide sufficient guidance to make a successful weld even though the exact composition may not be learned. Six of the different tests are summarized in Figure 15-13. This should be supplemented by Figures 15-1 and 15-2, which present physical and mechanical properties of metals.

Appearance Test

The first test is the appearance of the part. This includes features such as color and the appearance of the machined

FIGURE 15-13 Summary of identification tests of metals.

Properties / Base Metal or Alloy	Color	Magnet	Chisel	Fracture	Flame or Torch	Spark
Aluminum & alloys	bluish-white	non-magnetic	easily cut	white	melts wo/col	non-spark.
Brass, navy	yellow or reddish	non-magnetic	easily cut	not used	not used	non-spark.
Bronze, alum. (90Cu-9Al)	reddish yellow	non-magnetic	easily cut	not used	not used	non-spark.
Bronze, phosphor (90Cu-10Sn)	reddish yellow	non-magnetic	easily cut	not used	not used	non-spark.
Bronze, silicon (96Cu-3Si)	reddish yellow	non-magnetic	easily cut	not used	not used	non-spark.
Copper (deoxidized)	red; 1 cent piece	non-magnetic	easily cut	red	not used	non-spark.
Copper nickel (70Cu-30 Ni)	white 5 cent piece	non-magnetic	easily cut	not used	not used	non-spark.
Everdur (96Cu-3Si-1Mn)	gold	non-magnetic	easily cut	not used	not used	non-spark.
Gold	yellow	non-magnetic	easily cut	not used	not used	non-spark.
Inconel (76Ni-16Cr-8Fe)	white	non-magnetic	easily cut	not used	not used	non-spark.
Iron, cast	dull grey	magnetic	not easily chip.	brittle	melts slowly	see text
Iron, wrought	light grey	magnetic	easily cut	bright grey fib.	melts fast	see text
Lead	dark grey	non-magnetic	very soft	white; crystal	melts quick	non-spark.
Magnesium	silvery white	non-magnetic	soft	not used	burns in air	non-spark.
Monel (67 Ni-30Cu)	light grey	slightly magnet.	tough	light grey	not used	non-spark.
Nickel	white	magnetic	easily cut	almost white	not used	see text
Nickel silver	white	non-magnetic	easily chipped	not used	not used	non-spark.
Silver	white-pre 1965 10¢ pc	non-magnetic	not used	not used	not used	non-spark.
Steel, low alloy	blue-grey	magnetic	depends on comp	medium grey	shows color	see text
Steel, high carbon	dark grey	magnetic	hard to chip	very lgt. grey	shows color	see text
Steel, low carbon	dark grey	magnetic	continuous chip	bright grey	shows color	see text
Steel, manganese (14 Mn)	dull	non-magnetic	work hardens	coarse grained	shows color	see text
Steel, medium carbon	dark grey	magnetic	easily cut	very lgt. grey	shows color	see text
Steel, stainless (austentic)	bright silvery	see text	continuous chip	deps. on type	melts fast	see text
Steel, stainless (matensitic)	grey	slightly magnetic	continuous chip	deps. on type	melts fast	see text
Steel, stainless (ferritic)	bright silvery	slightly-magnet.		deps. on type		see text
Tantalum	grey	non-magnetic	hard to chip		high temp.	
Tin	silvery white	non-magnetic	usually as plating	usually as plating	melts quick	non-spark.
Titanium	steel grey	non-magnetic	hard	not used	not used	see text
Tungsten	steel grey	non-magnetic	hardest metal	brittle	highest temp.	non-spark
Zinc	dark grey	non-magnetic	usually as plating	at R.T.	melts quick	non-spark

as well as unmachined surfaces. The shape can be descriptive; for example, shape includes such things as cast engine blocks, automobile bumpers, reinforcing rod, I-beams or angle irons, pipes, and pipe fittings. Form should be considered and may show how the part was made, such as a casting with its obvious surface appearance and parting mold lines, or hot rolled wrought material, extruded or cold rolled with a smooth surface. Form and shape give definite clues. For example, pipe can be cast, in which case it would be cast iron, or wrought, which would normally be steel. Another example is a hot rolled structural shape in a steel-framed building, which would be mild or low-alloy steel.

Color provides a very strong clue in metal identification. It can distinguish many metals such as copper, brass, aluminum, magnesium, and the precious metals. On oxidized metals, the oxidation can be scraped off to determine the color of the unoxidized metal. This helps to identify lead, magnesium, and even copper. The oxidation on steel, or rust, is usually a clue that can be used to separate plain carbon steels from the corrosion-resisting steels.

The use of the metal part is also a clue to identify it. Many machinery parts for agricultural equipment and light and medium-duty industrial equipment are made of cast iron. For heavy-duty work such as brake presses, the castings would probably be steel. A railroad rail obviously can be identifed by shape and this gives an immediate clue to its composition.

Hardness Test

A second test that should be used is the hardness test. Portable instruments are available that can be taken to the work. This gives a hardness indication, which helps determine the type of metal.

A less precise hardness test is the file test. A summary of the reaction to filing and the approximate Brinell hardness and the possible type of steel is given in Figure 15-14. A sharp mill file is used. It is assumed that the part is steel and the file test will help identify the type of steel. Experience will help identify steel types with the file test.

Magnetic Test

The magnetic test can be quickly performed using a small pocket magnet. With experience it is possible to judge a strongly magnetic material from a slightly magnetic material. The nonmagnetic materials are easily recognized. The strongly magnetic materials include the carbon and low-alloy steels, iron alloys, pure nickel, and martensitic stainless steels. A slightly magnetic reaction is obtained from Monel and high-nickel alloys and the stainless steel of the 18% chrome–8% nickel type when cold worked, such as in a seamless tube.

File Reaction	Brinell Hardness	Type Steel
File bites easily into metal	100 BHN	Mild steel
File bites into metal with pressure	200 BHN	Medium carbon steel
File does not bite into metal except with extreme pressure	300 BHN	High alloy steel-high carbon steel
Metal can only be filed with difficulty	400 BHN	Unhardened tool steel
File will mark metal but metal is nearly as hard as the file and filing is impractical	500 BHN	Hardened tool steel
Metal is harder than file	600 + BHN	

FIGURE 15-14 **Approximate hardness of steel by the file test.**

The nonmagnetic materials are the copper-base alloys, aluminum-base alloys, zinc-base alloys, annealed 18% chrome–8% nickel stainless, the magnesiums, and the precious metals. With experience it is possible to use the magnetic test to help identify the various metals.

Chisel Test

The chip test or chisel test should also be used. The only tools required are a hammer and a cold chisel. The test is to use the cold chisel and hammer on the edge or corner of the material being examined. The ease of producing a chip is an indication of the hardness of the metal and if the chip is continuous it is indicative of a ductile metal whereas if chips break apart it indicates a brittle material. On such materials as aluminum, mild steel and malleable iron the chips are continuous. They are easily chipped and the chips do not tend to break apart. The chips for gray cast iron are so brittle that they become small broken fragments. On high-carbon steel, the chips are hard to obtain because of the hardness of the material, but they can be continuous.

Fracture Test

This test is simple to use if a small piece of the metal being evaluated is available. The ease of breaking the part is an indication of its ductility or lack of ductility. If the piece bends easily without breaking it is one of the more ductile metals. If it breaks easily with little or no bending it is one of the brittle materials. The surface appearance of the fracture is also an indication. It will have the color of the base metal without oxidation. This will be true of copper, lead, and magnesium. In other cases, the coarseness or roughness of the broken surface is an indication of its structure. A careful study of known metals,

how they appear at the fracture, will help build experience to identify unknown specimens.

Flame or Torch Test

A high-temperature flame such as the oxyacetylene torch flame is used. The flame test should be used with discretion since it is possible that it will damage the part being investigated. If at all possible it should be used on a small piece of the metal being checked. The factors learned from this test are the rate of melting, the appearance of the molten metal and slag, and the action of the molten metal under the flame. All these factors provide clues which can aid in making the evaluation. When a sharp corner of a white metal part is heated the rate of melting can be an indication. If the material is aluminum it will not melt until sufficient heat has been used because of the high conductivity of aluminum. If the part is zinc the sharp corner will melt quickly since zinc is not a good conductor. In the case of copper, if the sharp corner melts, it is normally deoxidized copper. If it does not melt until much heat has been applied, it is electrolytic copper. Also, with copper alloys, if lead is the composition, it will boil, indicating a lead-bearing alloy. To distinguish aluminum from magnesium, apply the torch to filings. Magnesium will burn with a sparkling white flame. Steel will show characteristic colors before melting.

Spark Test

This is a very popular and reliable test for identification of different steels. The test requires the use of high-speed grinding wheel, either fixed or portable. The grinding wheel should have a speed of at least 5000 surface feet per minute. The surface feet per minute equals the circumference in inches multiplied by the revolutions per minute divided by 12. Spark testing should be done in subdued light since the color of the spark is important. Spark testing is not used on nonferrous metals since they do not exhibit spark streams of any significance. This is one way to separate ferrous and nonferrous metals. For example, it can be used to separate stainless steel from high-nickel or copper–nickel materials, such as Monel, since sparks would be produced only by the stainless steel. It is advisable to have specimens or samples of known steels which can be sparked immediately before or after sparking the unknown material to help determine the unknown composition.

Spark testing has been thoroughly studied and data are available with photographs showing the sparks that are produced. The spark resulting from the test should be directed downward and studied. Figure 15-15 shows the sparks resulting from a spark test. The color, shape, length, and activity of the sparks relate to characteristics of the material being tested. The spark stream has specific items which can be identified. The straight lines are called

FIGURE 15-15 **Spark test.**

carrier lines. They are usually solid and continuous. At the end of the carrier line they may divide into three short lines which are called forks. If it divides into more lines at the end it is called a *sprig.* Sprigs also occur at different places along the carrier line. These are sometimes called bursts, either star or fan bursts. In some cases, the carrier line will enlarge slightly for a very short length, continue, and perhaps enlarge again for a short length. When these heavier portions occur at the end of the carrier line they are called spear points or buds. High sulfur creates these thicker spots in carrier lines and the spearheads. Cast irons have extremely short streams, whereas low-carbon steels and most alloy steels have relatively long streams. Steels usually have white to yellow color sparks while cast irons are reddish to straw yellow. By learning to identify the different portions of the spark, and by making tests on known samples it is possible to acquire experience sufficient to make relatively accurate determinations of the metal being investigated. The following is a summary of some metals and the type of spark that is produced.

Cast iron: dull red to straw yellow color, short spark stream, many small sprigs short and repeating.

Wrought iron: long straw-colored carrier lines, usually whiter away from the grinding wheel. Carrier lines usually end in spearhead arrows or small forks.

Low-carbon or mild steel: long yellow carrier line; occasional forks and lines may end in an arrowhead.

Low-alloy steel: each alloying element has an effect on the spark appearance and very careful observation is required. Type 4130 steel has carrier lines that often end in forks and sharp outer points with few sprigs.

High-carbon steel: abundant yellow carrier lines with bright and abundant star bursts.

- *Manganese steel:* bright white carrier lines with fan-shaped bursts.
- *Stainless steels:* The chrome–nickel steels give off short carrier lines, sometimes making a dotted line without buds or sprigs.
- *Nickel:* Extremely short spark stream. Carrier lines are orange. There are no forks or sprigs and the sparks may follow the grinding wheel.
- *Titanium:* A very white spark stream. Carrier lines are uniform in size and terminate in forks and in arrowlike shapes at an angle from the carrier line.

The spark atlas of steels by Tschorn[5] is by far the most comprehensive authority on this subject. It relates to various national standards and has numerous pictures illustrating the spark stream produced by each type of material.

Chemical Test

There are numerous chemical tests that can be made in the shop for identifying some materials. Monel can be distinguished from Inconel by one drop of nitric acid applied to the surface. It will turn blue-green on Monel but will show no reaction on Inconel. A few drops of a 45% phosphoric acid will bubble on low-chromium stainless steels. These tests can become complicated and for this reason are not covered here. Metal identification kits, designed for portable use, are helpful. They electrically remove a minute amount of the test metal onto a filter paper. Reagents in the kit placed on the sample give distinct colors identifying metallic elements. For more information refer to ASTM booklet, STP 550.[6]

The use of these methods coupled with samples of known metals and with experience will enable you to make identifications sufficiently accurate for most welding requirements.

15-4 HEAT AND WELDING

Heat is employed in most welding processes. The heat source for welding may be generated in at least the following different ways:

1. An electric arc maintained between an electrode and the work
2. Resistance heating obtained by passing high current through the parts to be joined
3. A high-temperature flame obtained by burning a fuel gas with oxygen using a torch
4. Mechanical sources from sliding friction, explosive impact, and ultrasonic vibrations
5. Exothermic chemical reaction producing superheated liquid metal
6. Radiation from a focused high-energy beam of electrons
7. Radiation from a focused high-energy electromagnetic beam of coherent light

Heat is used to melt the surface of the metal to be welded so that coalescence, the growing together, can occur. Heat is also used to melt the filler metal that is added to the welding joint.

The most common source of heat for welding is the electric arc. The arc is a continuously moving heat source. Even though it moves, steady-state conditions are established and the temperature distribution relative to the heat source is relatively stable. The electric arc was previously discussed and we have learned that it has a temperature of from 5000 to 20,000 °C.

There are numerous detrimental effects of welding heat. Some of the disadvantages are:

1. High residual stresses from a localized heating causes differential shrinkage stresses which may lead to warpage and distortion.
2. A reduction of ductility or a degree of hardening in the heat-affected zone may lead to cracking.
3. The deterioration of the toughness properties of the joint, primarily in the heat-affected zone.
4. Loss of strength in the heat-affected zone of certain work-hardened, quenched, and tempered materials.

The heat input–time–temperature relationship or thermal cycle of a weld cannot be precisely determined because there are so many variables involved. However, fairly accurate estimates can be made to predict or explain the effects of heat, from a specific welding process, on a given metal under practical conditions. The total heat input must be balanced to produce the desired weld. A complicating factor occurs when a *cold* filler rod is used in making the weld. Sufficient heat must be provided to melt the filler rod at the proper rate and add it to the molten puddle. It is estimated that the temperature of the molten steel in the puddle is 3500 °F (1930 °C). Extra heat is required, over and above the amount needed to melt the filler rod and the surfaces of the base metal, to compensate for the heat conducted away from the weld. It is necessary to control closely the amount of heat input while making a weld joint.

The heat developed by a moving arc can be calculated by the following:

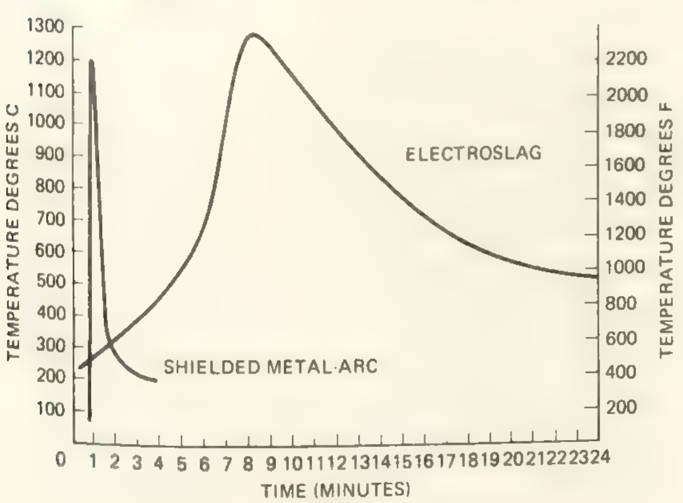
$$HE = \frac{E \times I}{S} \times 60$$

where HE = energy input in joules per linear measure of weld (inches or centimeters)
E = arc voltage in volts
I = welding current in amperes
S = travel speed in lineal measure per minute (in./min or m/min)

This energy input formula is used to calculate the heat developed in an arc and can be used in comparing welding procedures or for limiting heat input when welding quenched and tempered steels. Each welding process has a different thermal cycle. Figure 15-16 shows the time–temperature relationship of base metal taken immediately adjacent to welds made by two welding processes.[7] The rate of heat rise, the maximum temperature, the time at high temperature, and the rate of cooling of the metal are quite different for SMAW and ES welding. Processes with the highest concentration of heat cause the temperature to rise much more rapidly and to fall much more rapidly. The curve shown for the shielded metal arc weld rises almost instantaneously and the cooling rate of the base metal is a very steep slope indicating quick cooling. The curve for electroslag welding rises more slowly, holds at a high temperature for a fairly long time, and then decreases slowly. The temperature changes that occur during an arc welding operation are much quicker and more abrupt than for most metallurgical processes. The metallurgical reactions from welding heat do not follow the normal heat-treating relationships. The temperature changes with electroslag welding are more similar to those encountered in foundry metallurgy.

The increase of heat in a metal increases the atomic mobility in the metal. When sufficient heat is absorbed by a solid, it will change to a liquid. In welding, it is necessary to produce a liquid at the surface of the parts being welded. The heat source is removed to allow cooling so that solidification or coalescence occurs and a weld is made. Heat moves rapidly in metal from one area to another area whenever there is a difference in temperature. Heat will always move from the hot area to the cooler area. The welding heat source creates heat at a particular spot and is normally moving, at least in the arc processes. The heat is also moving so that a continually changing relationship occurs while welding. After an arc has stabilized it will approach thermal equilibrium but never quite reach it. The rate at which the heat flows to the cold area depends upon the conductivity of the base metal. Heat also moves by means of convection, by radiation, and by absorption; however, for practical purposes most of the welding heat flows by means of conduction. Therefore the conductivity of the metal has a large influence on heat input–output time cycle relationship.

FIGURE 15-16 Time-temperature relationship for different processes.



The temperature distribution around a point heat source can be shown by means of charts called *isotherms*.[8] These are lines that connect points of identical temperature. A typical temperature distribution curve made during the deposition of a shielded metal arc welding bead on thin material and on thick material is shown in Figure 15-17. This is the distribution of temperature around the arc with the arc at the highest temperature isotherm. The rise of the temperature, or the steepness of the curve, in front of the arc is much more rapid than the fall of temperature, or the slope of the curve, behind the arc. This is due to the instantaneous heat transfer from the arc and the longer time for the heat to be removed. The influence of the thickness of the base metal is shown by the illustration. Using identical welding conditions, a much wider flow of heat is created in the thinner plate than in the thicker plate. This is due to the mass of the thicker plate and the fact that the heat flows in three directions in it rather than in two directions for the thin material.

Not all the heat generated by the heat source is used in making the weld. This is shown by relating the heat input which is calculated by the formula shown, to the mass, or volume, of metal melted. The amount of heat required to melt a mass of metal is equal to the weight of the metal melted times the melting point (or degrees of temperature rise required) times the specific heat of the metal. It will be seen that from 20 to 75% of the energy available in the heat source is utilized in melting the metal. The percentage is different for different processes, procedures, base metals, base metal geometrics, and so on. For the shielded metal arc welding process 70 to 85% of the heat is utilized in making the weld nugget. For the carbon arc welding process 50 to 70% of the heat is utilized, while in submerged arc welding 80 to 90% of the heat generated by the arc is utilized in melting the weld metal. A major portion of this lost heat is used to raise the temperature of the base metal adjacent to the weld to near its melting point. Other losses come from weld spatter, heating the electrode and flux, and radiation and convection to the surrounding air.

In analyzing the effects of heat on a weld, a weld joint, or a weldment, it is necessary to determine:

1. The rate of heating
2. The maximum temperature attained
3. The length of time at temperature
4. The rate of cooling

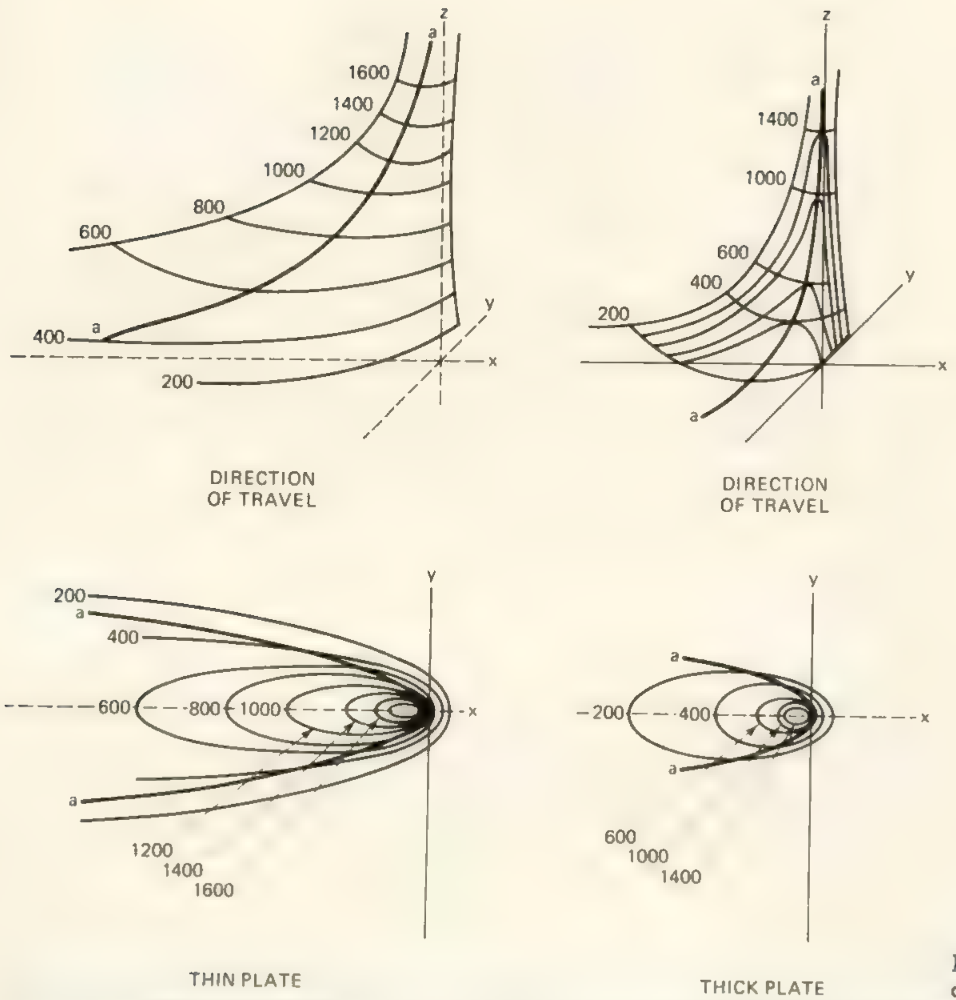


FIGURE 15-17 Temperature distribution around a moving arc.

These factors are difficult to determine; however, a good analysis of the potential damaging effects on the weld can be approximated. This allows precautions or procedure changes to minimize the harmful effects.

The *rate of heating* depends on a number of factors which include: the size and intensity of the heat source, the efficiency of the transfer of the heat to the base metal, the utilization of heat in making the weld, the mass of the base metal, the joint geometry, and thermal conductivity. How much heat is in the heat source and how fast does it flow from the weld area? For example, a low-current gas tungsten arc can be struck on a large thick copper plate and it would be impossible to make a weld since the temperature of the copper plate would not rise sufficiently to cause melting. Not enough heat is produced by the tungsten arc to melt the copper since the conductivity of the copper and its mass cause the heat to flow away so rapidly. The thermal conductivity, the ability to transmit heat throughout its mass, is of major importance when considering the rate of heating. Figure 15-1 provides the relative thermal conductivity of the common metals. Numbers cannot be put into formulas to provide exact answers; however, the relationship of thermal conductivity of one metal versus another provides a clue. For example, steel has only about a tenth of the thermal conductivity of copper. With reference to the isotherm diagram, the conductivity of the metal has an effect on the steepness of the curve or change of temperature gradient. Extremely steep temperature gradients occur in welding as a result of the high temperatures of the heat source and the temperature of the base metal. Steepness of the rate of the heating curve is much different for the different processes.

The *maximum temperature* that will be attained in the base metal is also important. The base metal at the weld must be raised to its melting temperature and above. How *much* above is important and depends on the welding process. Efficient welding does not require the base metal to be raised much above its melting temperature. The welding processes that utilize extremely high temperature heat sources such as electron beam or laser beam can raise the base metal temperature so high that it will volatilize the metal. This is why some processes can be used for both welding and cutting, depending on the heat input. When welding thin sheet metal with too much heat input, the material becomes too hot. It melts rapidly and

falls away, and holes are produced rather than welds. The maximum temperature reached by the base metal is related to the rate of heat input and to the rate of heat loss. As long as the heat input exceeds the rate of heat loss the base metal will continue to get hotter. This relationship must continue until surface melting of the base metal occurs.

Another factor is the *specific heat* of the base metal. This is a measure of the quantity of heat required to increase the temperature of the metal. It relates to the amount of heat required to bring the metal to its melting point. A metal having a low melting temperature but with a relatively high specific heat may require as much heat to cause surface melting as a metal with a high temperature melting point and a low specific heat. This can be seen by comparing aluminum to steel. The specific heat of the common metals is shown by Figure 15-1. The temperature required at the weld area should be only slightly greater than the melting temperature of the metal being welded. This is obtained in the base metal by balancing the heat input with the heat losses.

The length of time at the maximum temperature depends upon maintaining a heat balance between heat input and heat losses. There is rarely a true heat balance in any welding situation. During the arcing period, the heat input usually exceeds the heat losses and the base metal becomes hotter. Many times the welder must allow work to cool when the welding puddle becomes too large and unmanageable. The current is reduced or the arc is broken, and the heat input is reduced or ceases. The heat losses continue, and the puddle and base metal begin to cool. Normally the temperature of the work near the arc rises to a maximum. As soon as the arc moves on, the temperature adjacent to the weld begins to fall. The longer the base metal, adjacent to the weld, remains at a high temperature the greater the possibility for grain growth in the weld metal and in the heat affected area. The amount of metal melted, and the heat input and heat loss affect this relationship.

The *rate of cooling* of the weld and adjacent metal is the rate of temperature change from welding temperatures to room temperature. The rate of cooling can be closely controlled and is governed by such conditions as heat transfer, heat losses, and thermal conductivity of the base metal. However, several factors must be considered since they can be used to regulate the cooling rate. The most important one is the initial temperature of the base metal before welding. A higher preheat or the more heat in the weldment the slower it will cool. The second important factor is the heat input that may be given to the weldment after the weld is made. It is usually desirable to reduce the cooling rate if metallurgical problems such as cracking or hard zones occur. Hard zones in or adjacent to the weld usually have lower toughness and ductility and tend to crack when thermal stresses are introduced. By reducing the cooling rate these can be eliminated and quality welds produced. Factors that increase the heat input or the mass of heat, or reduce the heat losses will reduce the cooling rate, which will reduce the possibility of these defects.

15-5 WELDING METALLURGY

The science of joining metals by welding relates closely to the field of metallurgy. Metallurgy involves the science of producing metals from ores, of making and compounding alloys, and the reaction of metals to many different activities and situations. Heat treatment, steel making and processing, forging, and foundry all make use of the science of metallurgy. Welding metallurgy can be considered a special branch, since reaction times are in the order of minutes, seconds, and fractions of seconds, whereas in the other branches reactions are in hours and minutes.

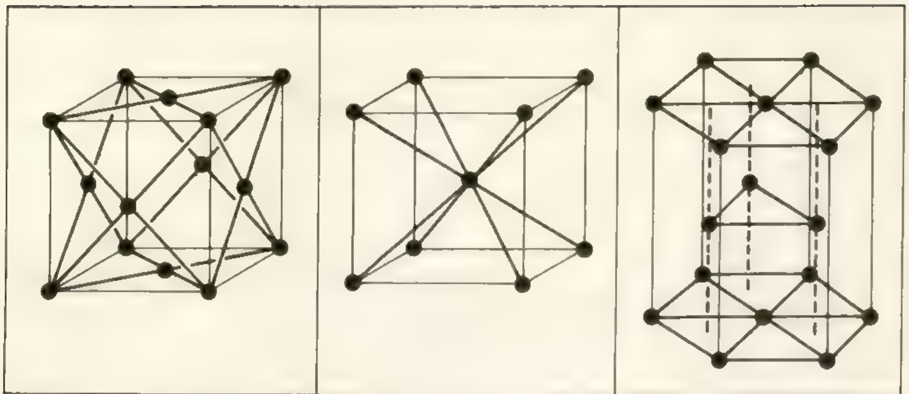
Welding metallurgy deals with the interaction of different metals and the interaction of metals with gases and chemicals of all types. The welding metallurgist is also involved with changes in physical characteristics that happen in short periods. The solubility of gases in metals and between metals and the effect of impurities are all of major importance to the welding metallurgist.

In a general treatment of welding such as this, many metallurgical factors and practices are found throughout the entire book. This chapter presents a very brief coverage of welding metallurgy.

The structure of metals is complex. When metal is in a liquid state, usually hot, it has no distinct structure or orderly arrangement of atoms. The atoms move freely among themselves within the confines of the liquid. Their mobility allows the liquid metal to yield to the slightest pressure and to conform to the shape of the container. This high degree of mobility of the atoms is due to the heat energy involved during the melting process.

As molten metal cools, the heat energy of the atoms in the liquid state decreases and the atoms move with less mobility. As the temperature is further reduced and the metal cools the atoms are no longer able to move and are attracted together into definite patterns. These patterns consist of three-dimensional lattices known as *space lattices*, which are made of imaginary lines connecting atoms in symmetrical arrangements. These imaginary lines are approximately the same distance from one another and limit the movement. Metals, in a solid state, possess this uniform arrangement, which is called *crystals*. All metals and alloys are crystalline solids made of atoms arranged in a specific uniform manner.

There are over a dozen types of space lattice possible; however, the majority of common metals fall into only three: (1) the face-centered cubic lattice, (2) the body-centered cubic lattice, and (3) the hexagonal close-packed lattice. The metals and the form of the crystal lattice structure are shown in Figure 15-18. Note that iron



Face Centered Cubic Crystal Structure FCC	Body Centered Cubic Crystal Structure BCC	Hexagonal Close Packed Crystal Structure HCP
Aluminum (Al) Copper (Cu) Gold (Au) Iron (Fe)—at intermediate high temperature Lead (Pb) Nickel (Ni) Platinum (Pt) Silver (Ag)	Chromium (Cr) Columbium (Cb) Iron (Fe)—at room temp and near melting temperature Molybdenum (Mo) Tantalum (Ta) Tungsten (W) Vanadium (V)	Cadminum (Cd) Cobolt (Co) Magnesium (Mg) Tin (Sn) Titanium (Ti) Zinc (Zn) Zirconium (Zr)

FIGURE 15-18 Crystalline structure of common metals.

has both the face-centered cubic structure and the body-centered cubic structure but at different temperatures. The change from one type of lattice structure to another takes place in the solid state with no change in specific gravity, but a small change in volume. This is known as an *allotropic change*.

The crystal lattices just mentioned are for pure metals that are composed of only one type of atom. Most metals in common use are alloys. In other words, they contain more than one metal. When more than one metal is present the atoms making up the crystals will change. The atoms of the metal making up the minor portion of the alloy will at random replace some of the atoms of the metal making up the majority of the alloy. If the crystals are of essentially the same size the minor metal will be considered to be dissolved in the major metal of the alloy. This condition is called a substitutional solid solution. A small amount of nickel added to copper will produce a substitutional solid solution.

If the atoms of the minor metal in the alloy are much smaller than those in the major lattice, they do not replace the atoms of the major metal in the lattice but rather locate in points between or in intervening spaces known as *interstices* in the lattice. This type of structure is called an *interstitial solid solution*. Very small amounts of carbon sometimes occur interstitially in iron.

If the minor metal atoms in the alloy cannot completely dissolve either interstitially or substitutionally, they will form the type of chemical compound the composition of which corresponds roughly to the chemical formula. This results in the formation of mixed kinds of atomic groupings consisting of different crystalline structures. These are referred to as *intermetallic compounds* and have a complicated crystal structure.

Each grouping with its own crystalline structure is referred to as a phase in the alloy and the alloy is called a multiphase alloy. The individual phases may be seen and distinguished when examined under a microscope at extremely high magnification.

These different alloys, solid solutions, intermetallic compounds, and phases occur as the molten metal solidifies. Freezing or solidification of a liquid metal does not happen simultaneously throughout the entire melt. Freezing begins at the point of lowest temperature just below the liquidus. At this point a small crystal forms, called a *nucleus*. Different nuclei may be formed almost simultaneously, and each is a point where solidification starts and the solidified metal grows from these points. The growth of solidification advances in all directions that are normal to the main axis of the nuclei crystal. Thus from a cubic crystal, growth progresses in six directions simultaneously. Growth is simply the adding on of additional crystals as temperature decreases. The growth continues and takes on a treelike pattern with branches and subbranches at right angles to one another. As solidification continues the branches become thicker and larger and fill the spaces between additional branches which are called *dendrites*. This continues until the entire mass has become solid. The dendritic growth of a crystal is shown in Figure 15-19.

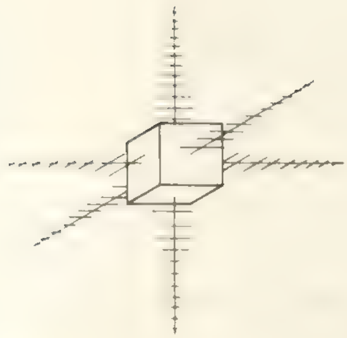
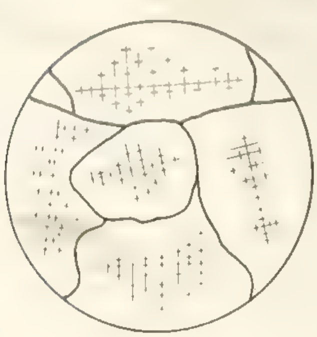


FIGURE 15-19 Dendritic growth from a nuclear crystal.

The crystals that grow from one nucleus can grow only to the point where they come in contact with another crystal growing from a different nucleus. Since the nuclei occur randomly, growth of dendrites from nuclei crystals are at odd angles with one another and this does not permit the various crystals to merge into a single crystal. The completely solidified metal is made up of individual dendritic crystals which are oriented in different planes but held together by atomic attractive forces at the interface of adjacent dendrites. When this resultant structure is cut in a flat plane, the individual dendritic crystals, which grew until they met adjacent dendritic crystals, form an irregularly shaped area, which is known as a *grain*. The fitting together of the different grains is normally in an irregular outline shape and the interface between grains is known as grain boundaries (Figure 15-20). Grains are also very, very small but much larger than the individual crystals.

The size of the crystals and the grains depends on the rate of growth of the crystal. The rate of crystal growth depends on the rate of cooling of the molten solidifying metal. When the rate of cooling is high, the solidification process occurs more rapidly and the crystal size and grain size tend to be smaller. When the rate of cooling is slower, crystal and grain size tend to be larger. With extremely slow cooling or possibly with reheating, grains that have crystal axis almost parallel with one another will tend to grow together and it is possible that two grains will grow into one.

FIGURE 15-20 Grains are formed by dendrites growing together.



Grains can also grow relatively long and narrow because of the orientation of the nuclei. Grain growths that have proceeded in primarily one direction are those at the edge of a groove weld. The crystal is formed and grows into elongated grains which produce a columnar structure. In restricted areas in which nuclei formed close together long grains are not possible and therefore more equiaxed grains result.

The overall arrangement of grains, grain boundaries, and phases present in an alloy is called its *microstructure*. The microstructure is largely responsible for the properties of the metal. It is affected by the composition or alloy content and by other factors such as hot or cold working, straining, heat treating, and so on. The microstructure of weld metal and adjacent metal is greatly influenced by the welding process and welding procedure, which influence the properties of the weld.

Anything done to the metal that will disturb or distort the lattice structure causes the metal to harden. Cold working of a metal distorts the structure and thereby hardens it. The presence of foreign atoms in the structure by alloy additions distorts the structure and tends to harden it. When atoms are dissolved in a solid state structure and are then precipitated out, the structure is distorted and is thus hardened.

The grain boundaries contain lower melting point materials since the grain boundaries are the last portion to freeze or solidify. The strength of metals is sometimes determined by the grain boundaries. Grain boundaries increase the strength of some materials at room temperature by inhibiting the deformation of individual grains when the material is stressed. At elevated temperatures the atoms in the boundaries can move more easily and slide past one another thus reducing the material strength. Fine-grained materials have better properties at room temperature. Metal structures can be characterized as having large grains (coarse grained) or small grains (fine grained) or a mixture of large and small (mixed grain size). The arrangement of atoms is irregular in the grain boundaries and there are vacancies or missing atoms. The atom spacing may be larger than normal and individual atoms can move more easily in the grain boundaries, and because of this the diffusion of elements, which is the movement of individual atoms through the solid structure, occurs more rapidly at grain boundaries. Odd-size atoms segregate at the boundaries and this leads to the formation of undesirable phases that reduce the properties of a material by lowering the ductility while making it susceptible to cracking.

Phase Transformation

Some metals change their crystallographic arrangement with changes in temperature. Iron has a crystalline body-centered cubic lattice structure from room temperature

up to 1670 °F (910 °C), and from this point to 2535 °F (1388 °C) it is face-centered cubic. Above this point, to the melting point of 2800 °F (1538 °C) it is again body-centered cubic. This change in crystalline structure is known as a *phase transformation* or an *allotropic transformation*. Other metals undergoing allotropic transformation at different temperatures are titanium, zirconium, and cobalt.

Another type of transformation occurs when the metal melts or solidifies. When the metal melts the orderly crystalline arrangement of atoms disappears and there is then random movement of atoms. When the metal solidifies the crystalline arrangement re-establishes itself. The change in crystalline structure or the change from liquid to solid is known as phase change. Pure metals melt or solidify at a single temperature while alloys solidify or melt over a range of temperatures with a few exceptions.

The phase changes can be related to alloy composition and temperature when they are in equilibrium, and shown on a diagram. Such diagrams are called phase diagrams, alloy equilibrium diagrams, or constitution diagrams. Metallurgists have developed constitution diagrams for almost every combination of metal alloys.[9] By means of these diagrams it is possible to determine the phases that are present and the percentage of each, based on the alloy composition at any specified temperature. In addition, it is possible to determine what phase changes tend to take place with increasing or decreasing temperature. Most constitutional phase diagrams describe alloy systems containing two elements. Diagrams of more than two elements are complex and difficult to interpret. Phase diagrams are based on equilibrium conditions. This means that the metal is stable at the particular point on the diagram based on relatively slow heating or cooling. In welding this is not true since temperature changes are extremely rapid and equilibrium conditions rarely occur. Even so, the constitution diagram is the best tool available to determine phases.

The Iron–Carbon Diagram

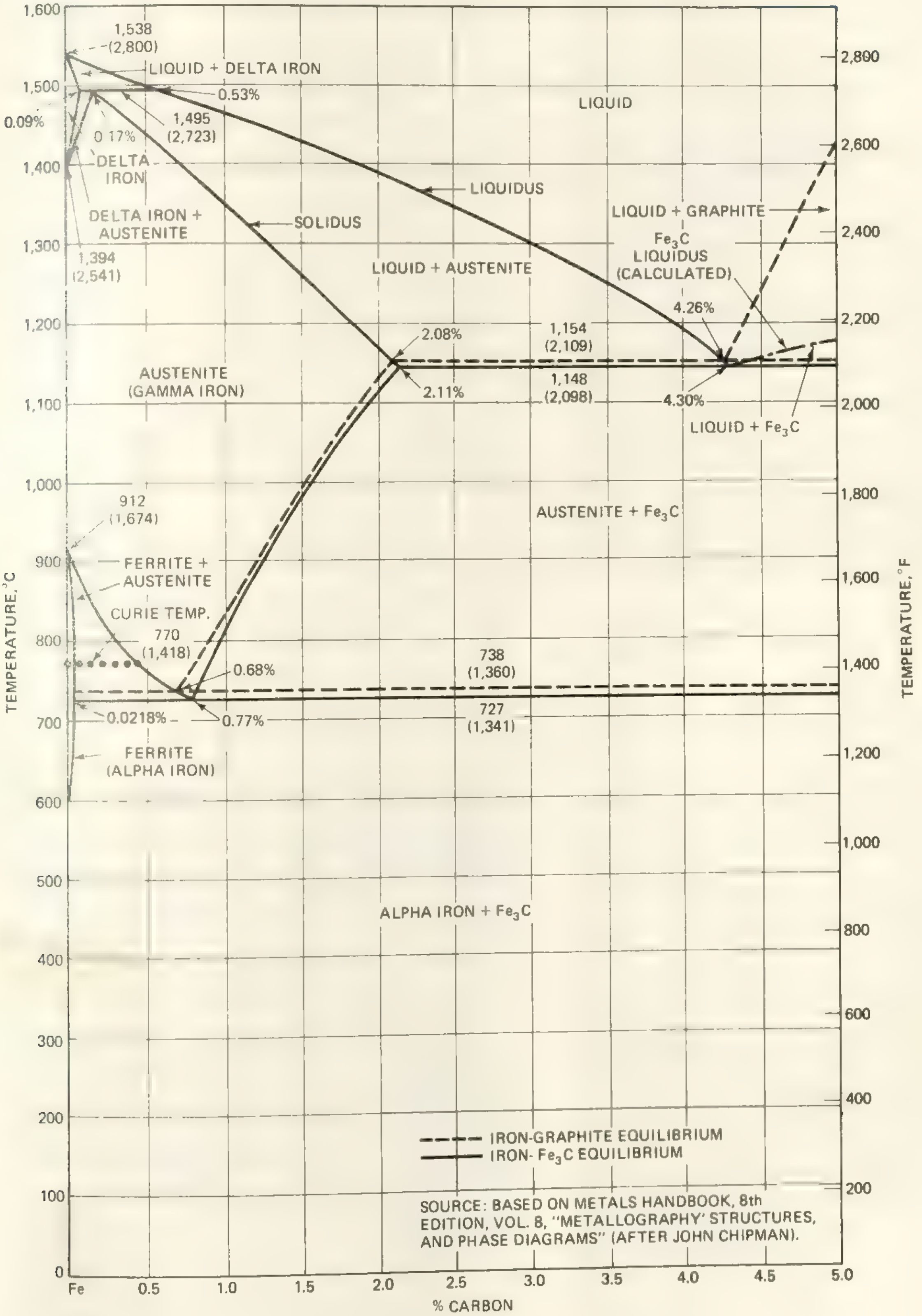
An understanding of the iron–carbon equilibrium diagram shown in Figure 15-21 will provide an insight of the behavior of steels in connection with welding thermal cycles and heat treatment. This diagram represents the alloy of iron with carbon, ranging from 0 to 5% carbon.

Pure iron is a relatively weak but ductile metal. When carbon is added in small amounts the iron acquires a wide range of properties and uses and becomes the most popular metal, steel. It was previously mentioned that iron has either of two crystalline structures, depending on temperature. This can be shown by the iron–carbon diagram by considering pure iron or 0% carbon. Above 2800 °F (1540 °C) the iron is in liquid state and there is no crystalline structure. Below this temperature, it solidifies and has a body-centered cubic lattice which is known as *delta iron*. As the temperature is further reduced below 2540 °F (1400 °C) a transformation occurs and the crystalline structure changes to a face-centered cubic arrangement known as *gamma iron*. Below 1670 °F (910 °C) the iron transforms back to the body-centered structure which is now known as *alpha iron*, and retains this structure down to room temperature. These transformation temperatures establish points on the iron–carbon diagram.

The other points and lines in the diagram show percentage of carbon involved in solid solution. Iron and carbon form a compound known as iron carbide (Fe_3C) or cementite. When iron carbide or cementite is heated above 2100 °F (1115 °C) it decomposes into liquid iron saturated with graphite. Graphite is a crystalline form of carbon. Most metals have the ability to dissolve other elements in the solid state and solid solutions are formed. Under suitable temperature and time conditions the dissolved elements will diffuse and homogenity will be obtained. A maximum solubility of carbon in alpha iron occurs at 1340 °F (727 °C) and decreases with lower temperature. This establishes a point on the diagram. A solid solution of carbon in alpha iron or delta iron (body-centered cubic) is known as ferrite. A solid solution of carbon in gamma iron (face-centered cubic) is known as austenite. As much as 2.1% carbon can be held in solid solution in gamma iron at a specific temperature and this establishes a point. In fact, the iron–carbon diagram can be divided at this point. Those alloys of iron and carbon less than 2.1% are considered steels, while those containing more than 2.1% are referred to as cast irons. Thus the line on the chart indicates whether or not the carbon is held in solid solution or whether it precipitates out.

To better understand the iron–carbon diagram consider a steel with a composition of 0.25% carbon. This would be indicated by drawing a vertical line between the 0 and 0.5% carbon line. Considering this line it will be seen that above approximately 2768 °F (1520 °C) the steel would be molten. As the temperature decreases delta iron would start to form in the liquid. At just below 2732 °F (1500 °C) it would transform to austenite and molten metal. However, at about 2696 °F (1480 °C) all the liquid metal would be solidified and it would be austenite. At approximately 1500 °F (815 °C) the austenite commences to break down and form a new phase at the grain boundaries. This new phase is almost pure iron or ferrite. Ferrite formation would continue until a temperature of 1340 °F (727 °C) was reached. At this point, the remaining austenite disappears completely, transforming to a structure known as pearlite plus ferrite. Pearlite is a mixture of ferrite and cementite and this structure would be retained down to room temperature. Microstructure of

FIGURE 15-21 Iron–carbon equilibrium diagram. (After *Metal Progress Data Book*, ©American Society of Metals, 1977.)



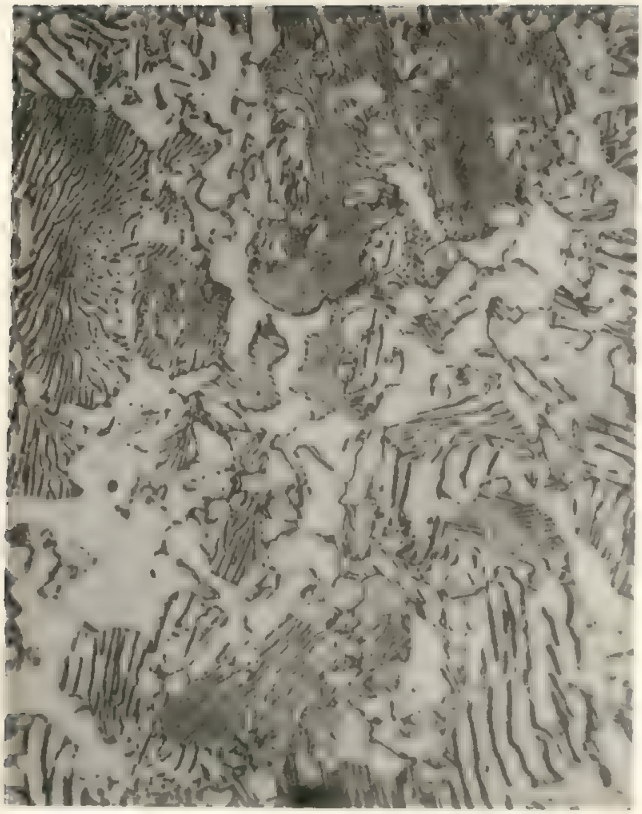


FIGURE 15-22 Pearlite micro structure.

pearlite is shown in Figure 15-22. Only the room-temperature structures can be seen and analyzed through a microscope.

By means of alloy additions it is possible to have the other structures at room temperature. The microstructure of pearlite is a lamellar structure which is relatively strong and ductile. The transformation during the cooling cycle will be reversed during the heating cycle. In welding the rise and fall of temperature or the rate of change of temperature is so fast that equilibrium does not occur. Therefore, some of the structures and temperatures mentioned here will be different. For example, if the cooling rate is faster, the austenite-to-ferrite transformation will be appreciably lower in temperature and this will also be true of pearlite. The pearlite will be more finely laminated since the transformation temperature is much lower. With extremely fast cooling rates the austenite might not have sufficient time to transform completely to ferrite and pearlite and will provide a different microstructure. In this case, some of the untransformed austenite will be retained and the carbon is held in a supersaturated state. This new structure is known as martensite and is shown in Figure 15-23. Martensite has a needlelike appearance and if the cooling rate is sufficiently fast the austenite might transform completely to martensite. Martensite is harder than pearlite or the pearlite–ferrite microstructure and it has lower ductility. Its hardness depends on the carbon content. Thus, it can be seen that the cooling rate influences the microstructure and causes higher hardness. This is because the crystal lattice is changed or distorted and this in turn hardens the material.

By adding different alloys to the steel the tendency of austenite to transform into martensite upon cooling increases. This is the basis of hardening steels. By proper use of different alloys the amount of martensite produced can be changed. The rate of cooling changes depending on the method of quenching. The more severe quench will create more martensite, and the slower quench will create less martensite and thus a lower hardness. The amount of alloys and their power to create this microstructure transformation is known as ***hardenability***. This is an advantage for heat treatment but can be detrimental to welding since high hardness is not desired in welds of softer materials.

The lines on the iron–carbon diagram show the different phases of iron–carbon alloy and indicate the microstructure of each phase. With respect to the iron–carbon alloy only pearlite and ferrite and pearlite and cementite (Fe_3C) are found at room temperature. However, in other iron–alloy systems other microstructures exist at room temperature. Ferrite is an example. Ferrite is a solid solution of carbon in delta or alpha iron. It has a body-centered cubic structure and occurs when less than 0.08% carbon is dissolved in the iron. It is the softest

FIGURE 15-23 Martensite micro structure.

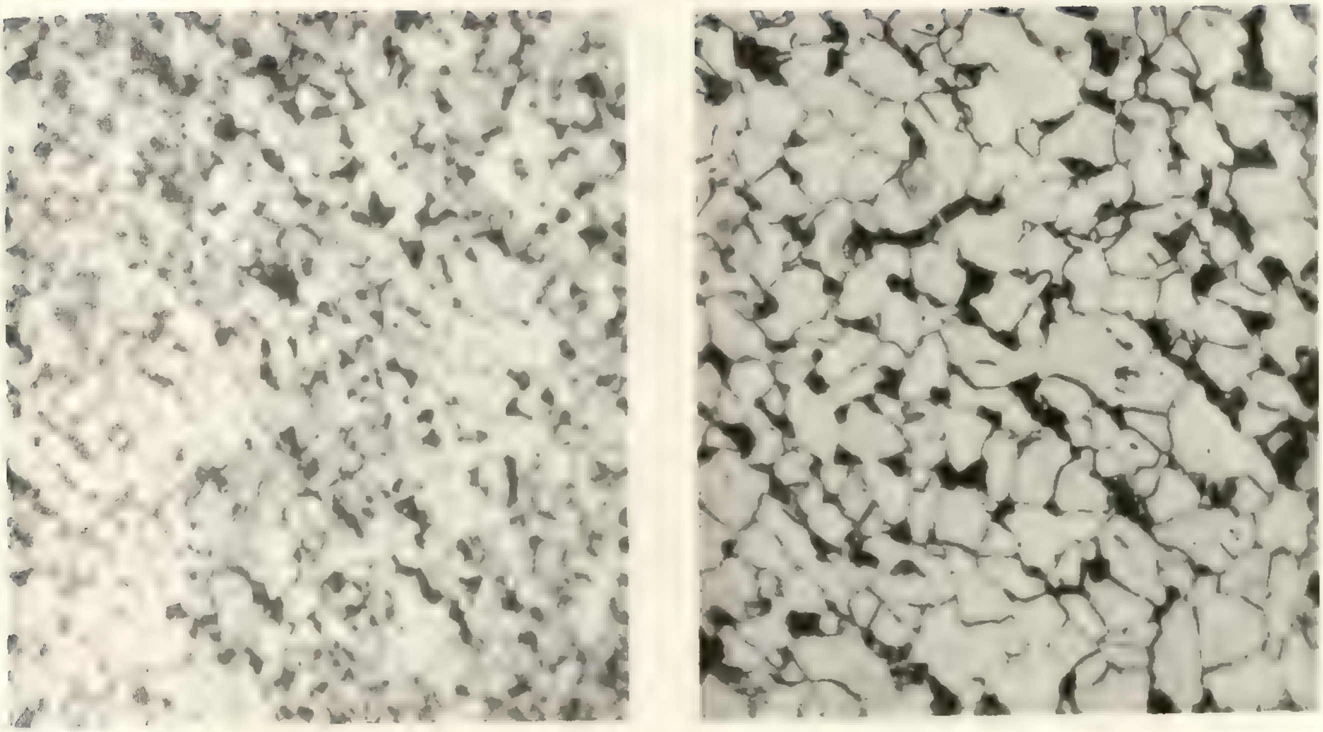


FIGURE 15-24 **Ferrite micro structure.**

constituent in steel and as the amount of ferrite increases the steel is softer. In alloy steels, certain alloy elements may be dissolved in ferrite as a solid state solution so that it occurs at room temperature. The microstructure of ferrite is shown in Figure 15-24.

The microstructure cementite (Figure 15-25) is hard and wear resistant and the composition will be varied when other carbide-forming alloys are present. It appears in several different ways, sometimes as a network surrounding the grains in the region of grain boundaries and also within the grains. It may also appear as round, roughly globular-shaped particles in steel that has been specially heat treated.

FIGURE 15-25 **Cementite micro structure.**

Austenite is another important constituent. It is the face-centered cubic lattice form and occurs in low-carbon steels in temperatures above 1333 °F (722 °C). It is not stable at room temperatures in carbon steel; however, in highly alloyed steels and stainless steels it is stable at room temperature. It has good tensile strength and is ductile, but it has a strong tendency to work-harden and is shown in Figure 15-26. There are other microstructures in steels; however, the foregoing are the most important.

Hardenability

The heat treatment of steels to increase hardness and the metallurgy of welding have much in common. Heat treating to increase hardness is accomplished by heating followed by rapid cooling. The rapid cooling of metal in and adjacent to a weld is in this same order. An under-

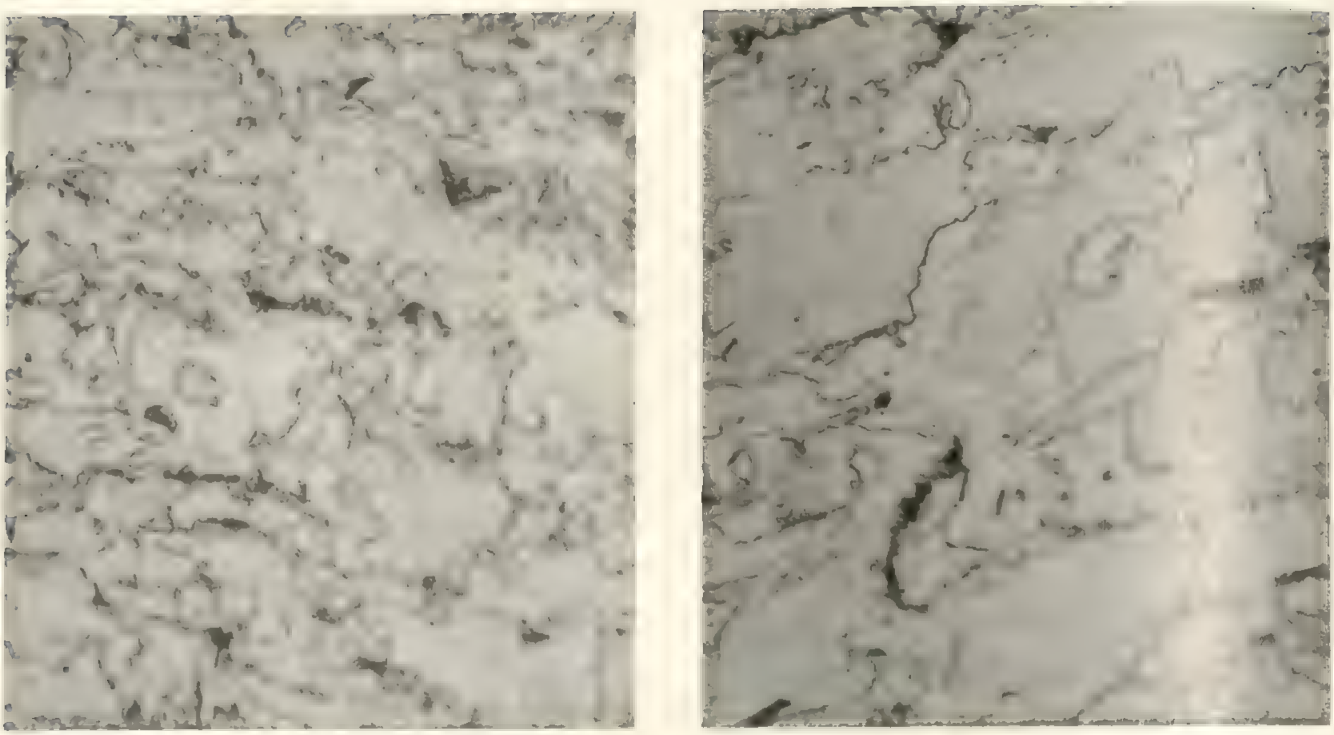


FIGURE 15-26 Austentite micro structure.

standing of hardening by heat treating will make the metallurgical changes during welding clearer. Most steels possess the property of hardenability, which is defined as the property that determines the depth and distribution of hardness induced by quenching. This property can be measured by the end quench test. In this test, a round bar is heated to a temperature in the austenite range and is then placed vertically in a fixture and a jet of water is directed upwards to the bottom end. The bar rapidly cools to room temperature. Hardness measurements are then made along the bar from the quenched end to the unquenched end and plotted against distance. This produces a curve with the high hardness at the quenched end and dropping off to normal hardness at the unquenched end. This hardenability curve shows the maximum hardness, the depth of hardness, and so on, under standardized conditions. It is very useful in establishing heat treating procedures. This information also provides data for welding since it indicates the effect of different alloying elements on the hardness of the quenched steel. The microstructure of the quenched steel can also be studied and related to the microstructure of welds.

Grain size and microstructure relate directly to hardness and strength. It was mentioned previously that as crystals deform they become harder and it is the growth of crystals that dictate grain size. In heat treating the steel is heated above the critical temperature, a phase change occurs, and new grains will nucleate and grow within the old grains. Since new grains of austenite were formed within each of the former grains the steel now has more finer grains. Fine grain size promotes both increased strength and hardness.

Alloying elements are added to steel to increase its hardenability. Carbon is the most important and effective, and small amounts will greatly increase hardness up to about 0.65%. Manganese is the next most important. Chromium and molybdenum also increase hardenability. These alloys contribute to other properties as well.

The time required for transformation of steel to begin and end at any constant temperature is a useful measure of the heat-treating characteristics of the steel. This can be shown by diagrams known as isothermal transformation diagrams, which plot temperature against time in seconds. Diagrams are available for steels of different composition and they show the phases that occur at different temperatures and times. The lines are constructed from experimental data and show the process of transformation at each temperature. Isothermal diagrams help to explain the relationship between cooling rates and the microstructure of a specific steel composition. During cooling the steel remains a certain period of time in each phase and the time period is inversely proportional to the cooling rate. With very slow cooling rates the phase changes take place near equilibrium values. As the cooling rate is increased time is reduced so that there is not enough time for completion of the pearlite reaction and some austenite remains below the equilibrium transformation temperature which creates hardening. The cooling rate must be so rapid that much of the austenite transforms to martensite rather than pearlite. These curves are

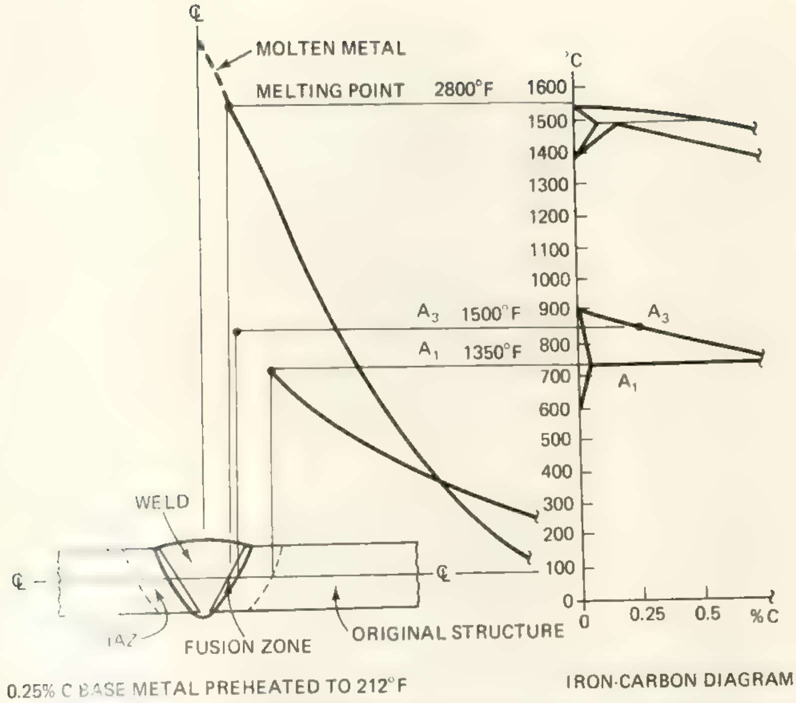


FIGURE 15-27 **Temperature distribution at a weld.**

of limited use in welding but do show the types of transformation occurring at subcritical temperatures and their effects.

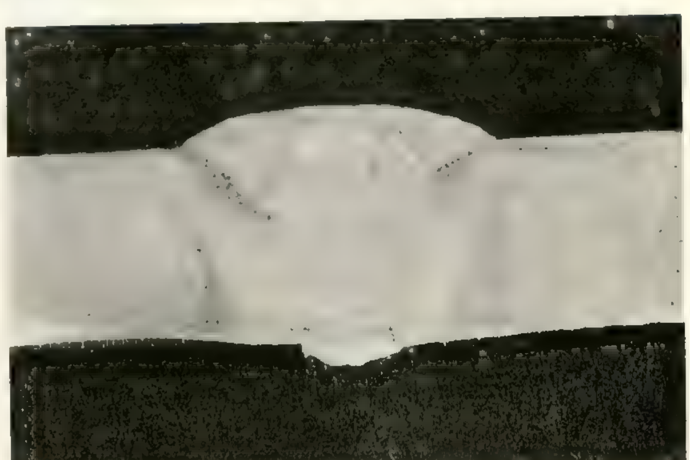
Welds

When a weld is made all the factors just mentioned occur: the changes of temperature, the changes of dimensions, the growth of crystals and grains, the phase transformation, and so on. The type of welding process dictates, in general, how these will occur. In the arc welding processes the heat cycle is of primary importance. The previous section explained the heat input time-temperature relationship or thermal cycle. The rate of cooling or quench is of primary importance and this is controlled by the process, procedure, metal, and mass. The electroslag process has the slowest cooling rate while the gas metal arc has a much faster cooling rate. The rate of change decreases as the distance from the center of the weld increases (Figure 15-27). It is obvious that many different cooling rates occur and that different microstructures will result. This is shown in Figure 15-28, which is a multipass groove weld. The different structures that occur in the weld are shown, as well as the different phases shown in the base metal adjacent to the weld.

With any arc process, where metal is transferred across the arc, the metal reaches a superheated temperature much above the melting temperature shown on the iron–carbon diagram. When it is deposited in the weld it is molten or in the liquid phase. Immediately the weld metal starts to freeze or solidify. The heat contained in the molten metal is transmitted to the base metal and its temperature at the weld is raised to the molten stage. Away from the weld the metal is raised to a lower temperature. This creates a multitude of time–temperature curves based on location. As the weld metal freezes, the crystals form into grains which rapidly cool until there is no more liquid metal. The cooling rate is much faster than occurs in a casting or ingot and therefore, equilibrium, as represented in the iron–carbon diagram, really does not occur.

In addition to the complications created by the rapid cooling there is also the complication of composition variations. As weld metal is deposited on base metal some of the base metal melts and mixes with the weld metal, producing a dilution of weld metal. Unless the composition of the deposited filler metal and the composition of

FIGURE 15-28 **Cross section of a multipass arc weld.**



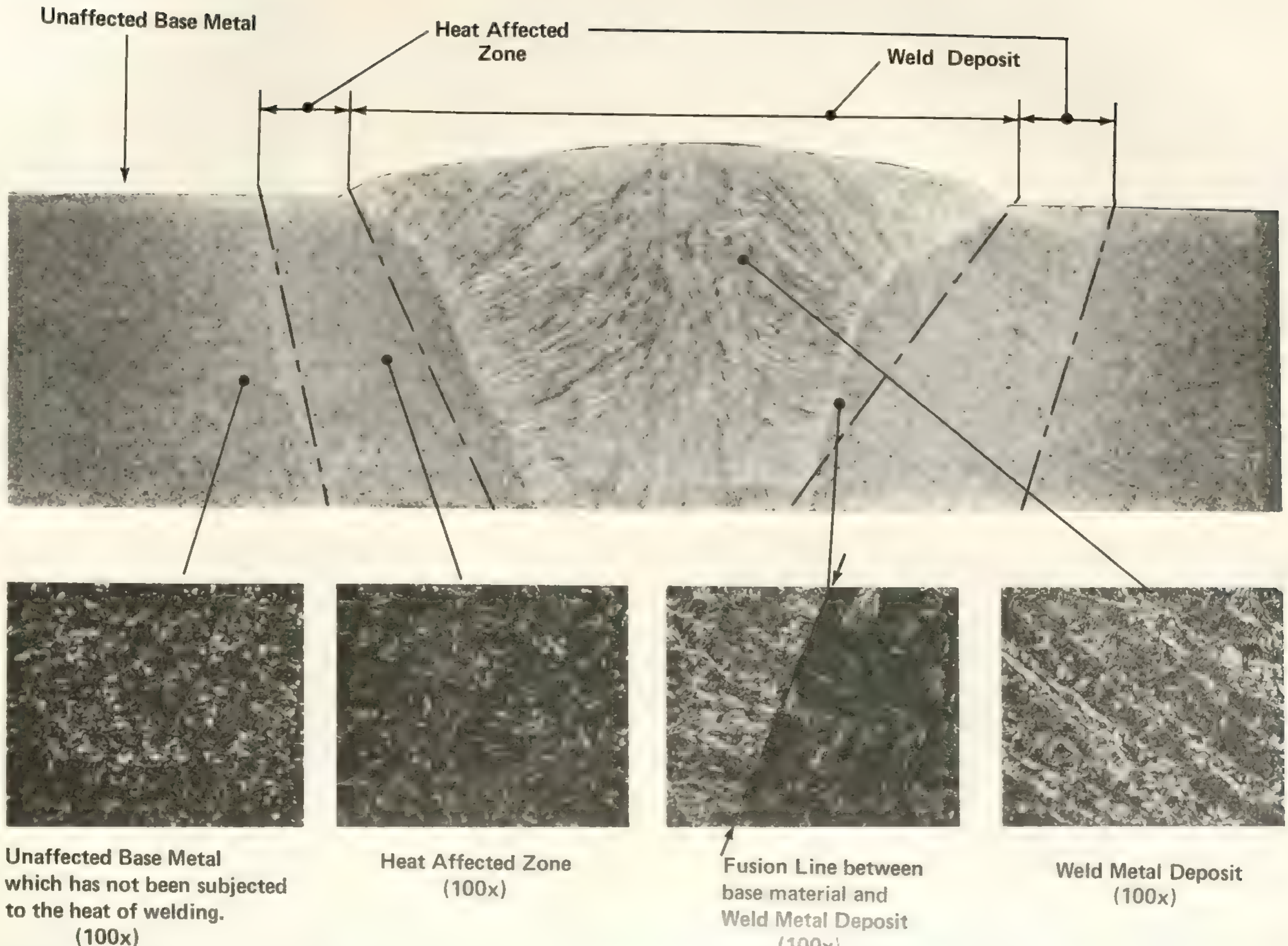


FIGURE 15-29 Micro structure at different parts of a weld.

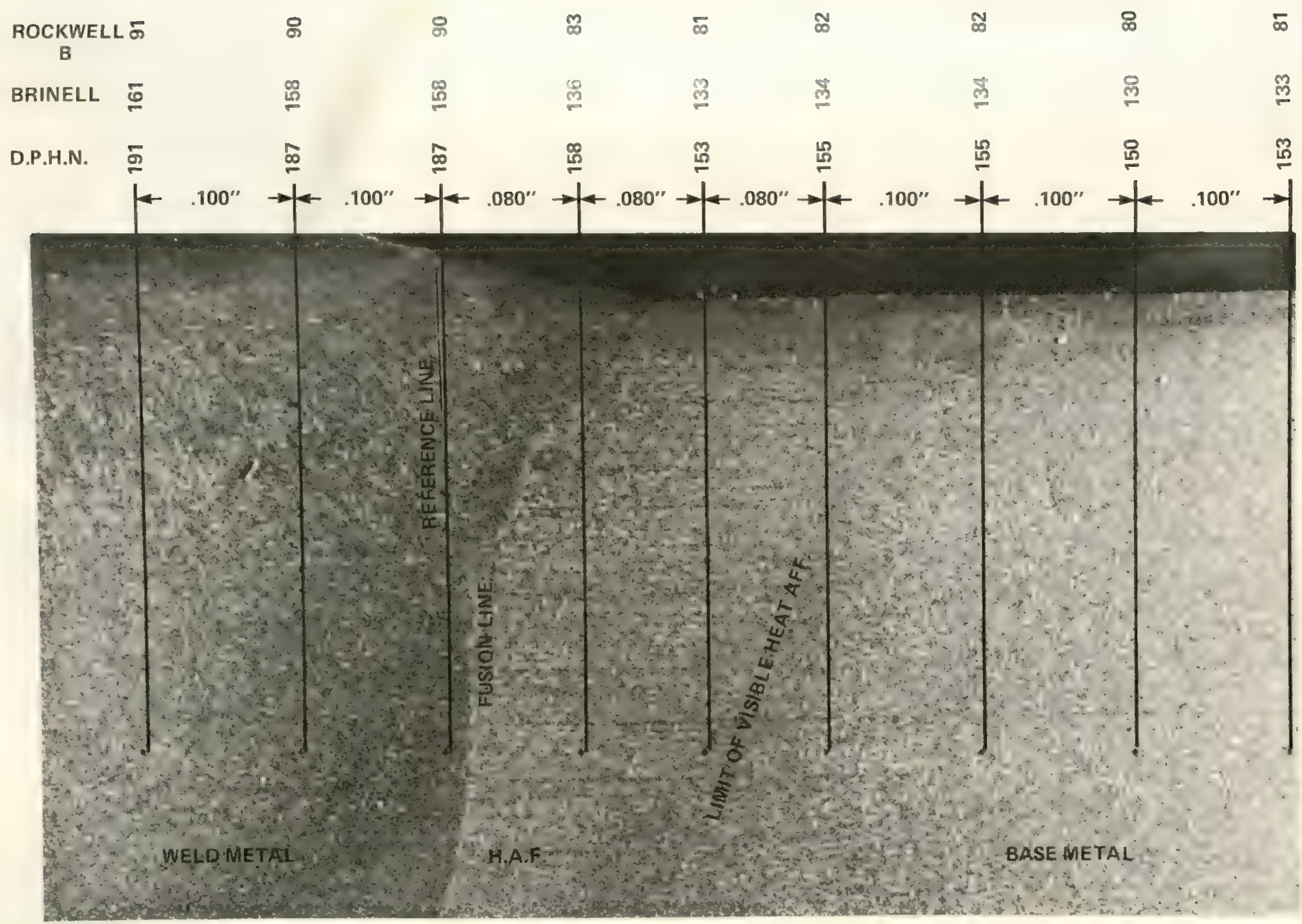


FIGURE 15-30 Macro structure and hardness across arc weld interface.

the base metal are identical there will be a variation of composition of the metal at the interface. In multipass welds, the first pass will have a high dilution factor, the second pass less, and the third pass perhaps little or none. When welding on a base metal with a different composition from the deposited metal this variation can be considerable. Variation in composition and the variation in the cooling rates will create variations in microstructure as shown in Figure 15-28. This is the reason that the microstructure of the weld is important and should be studied. The microstructure taken at different locations in the weld is shown in Figure 15-29. Each microstructure has its particular characteristics, as previously discussed. One of the important characteristics is the hardness of the microstructure throughout the weld area. The hardness should not vary over specific limitations. Figure 15-30 shows the macrostructure of a weld metal–base metal interface and the hardness at different points across this interface. Note the higher hardness of the weld metal compared to the base metal and that in the heat-affected zone the hardness is between these two values. This macrograph is of a low-carbon base metal joined with slightly alloyed weld metal.

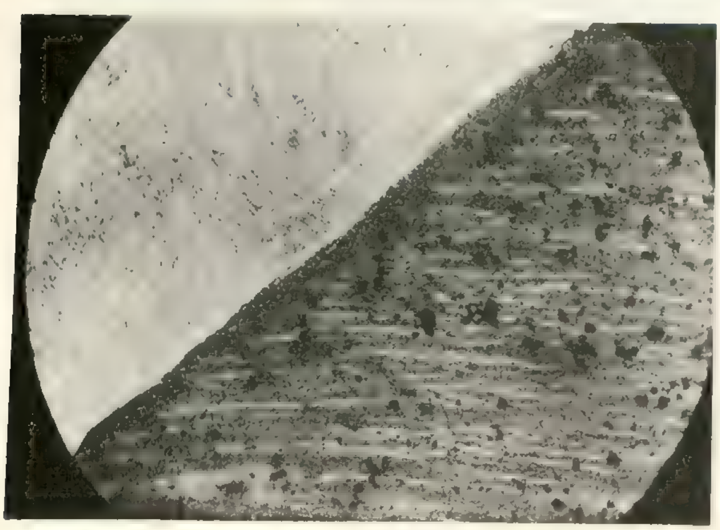
The area between the interface of the deposited weld metal, and extending into the base metal far enough that any phase change occurs, is known as the *heat-affected zone* (HAZ). This is shown in several of the pictures. The heat-affected zone, while part of the base metal, is considered to be a portion of the weld joint since it influences the service life of the weld. The heat-affected zone and the admixture zone are the most critical in many welds. For example, when welding a hardenable steel the heat-affected zone can increase in hardness to an undesirable level. On the other hand, when welding a hardened steel the heat-affected zone can become a softened zone since the heat of the weld has annealed the hardened metal. In the case of electroslag welding, the heat-affected zone will contain extremely large grains because of the long time at high temperature and the possibility for grain growth. The hardness of the weld metal, the base metal, and the heat-affected zone of an electroslag weld will be relatively uniform.

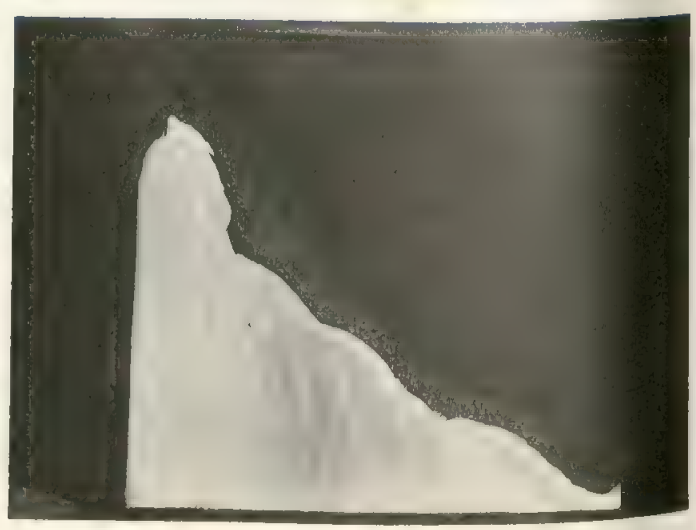
When the base metal and weld metal are of completely different analysis the interface zone contains alloys that can be detrimental. Figure 15-31 shows the interface between a low-alloy high-strength steel and a stainless steel weld. Note the heat-affected zone of the base metal and the minute amount of mixing of the lighter colored stainless steel deposit with the base metal. In this case, the alloy mixture produced is of such a small amount that it does not have an appreciable effect on the overall properties of the weld joint.

Another problem of the weld is the segregation during the thermal cycle. Segregation relates to the solubility of elements in metals, particularly alloys. The composition of the first crystals which form as an alloy freezes is different from the composition of the liquid that freezes last. The purer metals have the higher melting point or freezing point and therefore, freeze first. Metals or elements with lower melting points freeze last. In addition, in weld metal, because of the rapidity of freezing time, very little diffusion occurs and there is a lack of homogeneity in the total weld. Carbon, phosphorus, sulfur, and sometimes manganese are frequently in the segregated state in steel. This can be determined by high-magnification study of the microstructure. Segregation, particularly of carbon, can be partially dispersed by means of heat treatment.

Molten metal has a relatively high capacity of dissolving gases in contact with it. As the metal cools it has less capacity for dissolved gases and when going from liquid to solid state the solubility of gas in metal is much

FIGURE 15-31 Interface of dissimilar weld joint.





lower. The gas is rejected as the crystals solidify but it may be trapped because of almost instantaneous solidification. Entrapment of the gas causes gas pockets and porosity in the weld. Carbon monoxide which is present in many arc and fuel gas atmospheres is sometimes trapped. Hydrogen that may be present in the arc atmosphere is also trapped. Hydrogen, however, will gradually disperse and escape from the weld metal over a period of time. High temperatures increase the speed for hydrogen migration and removal. The inert gases are not soluble in molten metal and for this reason are used in many gas-shielded applications.

The solubility of metals within metals is also of high interest, particularly for dissimilar metal welding. The solubility is determined by the equilibrium diagram of the alloys. The greater the degree of solubility, the better the success of welding dissimilar metal combinations.

It is impossible to provide a more thorough coverage of the metallurgy of steel welds in the space available. For more information, see Refs. 10 to 12.

The metallurgy of nonferrous metals resembles but is quite different from the metallurgy of iron and steel.

15-6 WELDABILITY OF METALS

The American Welding Society defines weldability as "the capacity of a material to be welded under the fabrication conditions imposed into a specific suitably designed structure and to perform satisfactorily in the intended service." This definition includes many qualifying statements, for example, "is the design suitable?" and "is the material suitable?" And what about the welding process and the welding procedures? A more practical definition might be "the ease with which a satisfactory weld can be made that will produce a joint equal to the metal being welded."

It has been stated that all metals are weldable, but some are much more difficult to weld than others. In view of this, it is vitally important that the welding process and welding procedures be considered when determining the weldability of a particular metal.

In any of these definitions it is important to know all about the metals to be welded, the design of the welds and the weldment, and the service requirements including loadings and the environment to which it will be exposed. Perhaps the best definition is that a weldable material can be welded so that the joint is equal in all respects to the base metal—in other words, a 100% weld joint.

The base metal or metal to be welded must be considered from all points of view. This includes its physical properties, mechanical properties, and chemical composition and structure.

The physical properties are not always identical in materials of the same composition. This relates to the size of the test specimen, method of testing, and the type of microstructure. The mechanical properties can be different for different materials even though they may fall within the same specification or class. For example, hardness is related to structure which is affected by thermal history or heat treatment. The direction of testing has a large effect on strength levels, toughness, and ductility. In addition, composition and microstructure may vary. In heavy material, the composition may have more carbon or alloy to provide the strength called for by the specification, and the structure will change from the outside to the center based on different rates of cooling when the material was produced.

It becomes apparent that materials may not be as uniform or consistent as we have thought. Segregation and changes in metallurgical structure affect the properties. Despite this, we must still produce the weld or weldment that provides the required service performance. To better determine weldability, it becomes necessary to make several assumptions:

1. The material to be welded is suitable for the intended use. In other words, it will provide the proper and necessary properties to withstand its service requirements.
2. The design of the weldment is suitable for its intended use. In considering the design for the weldment we should include the design of the welds.

Based on these assumptions, it is necessary then to study the weld joint. The desirable weld joint has uniform strength, ductility, notch toughness, fatigue strength, and corrosion resistance throughout the weld and adjacent material.

Most welds involve the use of heat and the addition of a different metallurgical structure from the unaffected base metal. Welds may also include defects such as voids, cracks, and entrapped materials. Two types of problems may occur:

1. Problems of the weld metal deposit or heat-affected zone that occur in connection with or immediately following the welding operation, such as hot cracking, heat-affected zone cracking, hydrogen-induced cracking, and so on.
2. Problems in the weld or adjacent to the weld that occur any time during service of the weldment. These can be any kind of defects that will reduce the efficiency of the weld joint under service conditions.

It is our objective to produce a weld that will avoid the problems. Hot cracking may result from any of the following four factors: restraint, weld shape, excessive heat input, or material composition. It can result from any one factor but is much more likely if two or more factors are present.

Restraint is always present in any weld because as the weld solidifies it acquires strength but continues to cool and shrink. It is the degree of restraint that becomes critical. Restraint relates to the weld design, the weldment design, and the thickness of the materials being joined.

Weld shape is also a function of weld design, weldment design, and welding procedure. Weld procedure relates to the placement of welds or beads in the weld, the shape of the beads, and the shape of the finished surface of the weld.

The third factor is the metal composition. Segregation is important, however, since impurities such as sulfur and phosphorus tend to form low-melting-point films between solidifying grains of the metal. These impurities relate to weld joint detail and the welding process, since they affect the amount of dilution. Lamellar tearing is also associated with base metal impurities and its through-directional strength. When the degree of restraint increases, as it does in thicker metals, this problem becomes more serious.

Hydrogen cracking is considered cold cracking since it occurs soon after the weld is completed, usually within 4 to 8 hours. It usually occurs in the heat-affected zone. It may occur while the weld is cooling down to room temperature. The four main factors that affect heat-affected zone cracking are:

- □ The thickness of the base metal and the type of weld
- □ The composition of the base metal
- □ The welding process and filler metal type
- □ Energy input and preheat temperatures

The effects of these four factors are interrelated. The thickness of composition of the base metal is established by the design. The weld joint configuration, the welding process, the type of filler metal, and the welding procedure can all contribute to the severity of the factors that cause HAZ cracking. The input energy can be modified by the welding process, welding procedure and the welding preheat temperature. These can also be changed to reduce the cooling rate.

All of the factors above determine the type of microstructure that will occur in the heat-affected zone. The two factors most important to weldability are hardenability and the susceptibility of the hardened structure to cracking. Both are increased by using a higher carbon or higher alloy content in the base metal. Certain alloying elements increase hardenability without a significant increase in the susceptibility to cracking. In this regard the carbon equivalent of the base metal becomes important. The carbon equivalent formula[13] is shown in Figure 15-32.

Plain carbon steels which have a carbon equivalent of not over 0.40% are considered readily weldable. This carbon equivalent can be increased up to 0.45% provided that the carbon does not exceed 0.22%, the phosphorus

$$\text{C.E.} + \text{C\%} + \frac{\text{Mn\%}}{6} + \frac{\text{Ni\%}}{20} + \frac{\text{Cr\%} + \text{Mo\%}}{10} + \frac{\text{Cu\%}}{40}$$

FIGURE 15-32 Carbon equivalent formula.

does not exceed 0.06%, and the steel is not over 3/4 in. (19.1 mm) thick.

Usually when the carbon equivalent exceeds 0.40%, special controls are required. The low-hydrogen processes or filler metals should be employed. Higher heat input should be employed and preheat may be required. When the carbon equivalent exceeds 0.60%, low-hydrogen processes are required; preheating is required if the thickness exceeds 3/4 in. (19.1 mm).

Hardenability is related to the cooling rate of metals. The faster cooling rate tends to produce higher hardnesses. The cooling rate depends on the mass of the metal, the welding process, the welding procedure, and preheat temperatures. The welding process and procedure influence the energy input used to make the weld. The greater the energy input, the slower the cooling rate. Heat input is a function of welding current, arc voltage and travel speed. To increase the heat input, increase the welding current or reduce the travel speed. Welding current relates to process and to electrode size. Heat input is calculated by using the formula given previously.

Thus, by increasing amperes or voltage, heat input increases but by increasing travel speed heat input decreases. The voltage has minor effect since it varies only slightly compared to the other factors. In general, higher heat input reduces cooling rate. This must be used with caution since on quenched and tempered steels too high a heat input will tend to soften the heat-affected zone and its strength level will be reduced.

In steels of relatively low hardenability it is possible to produce an unhardened heat-affected zone by increasing the heat input. In higher hardenability steels, the tendency toward cracking, and the maximum hardness, will be reduced by a slower cooling rate. There are limits to the amount of heat input that can be used. In this case, preheating is used in order to reduce cooling rates.

There is an interplay of several variables in regard to hydrogen cracking. These are the base metal composition, the heat input, the preheat temperature, the rate of cooling, and restraint. On a nonhardenable thin material the control of hydrogen is not important. As carbon and alloy increase, to provide greater hardenability, and as thickness increases the effect of hydrogen becomes of vital importance.

Heat-affected zone cracking depends on many of the same factors just mentioned. There are, however, general precautions that should be taken with certain types of steels to avoid HAZ cracking. Constructional

steels can be grouped into five general classifications depending on whether or not they are hardenable and the nature of the hardened structure. These must be tempered with the effects of thickness which increases restraint and adds to the cracking problem. The five classes are:

1. Nonhardenable low-carbon mild steel.
2. Low hardenability with low susceptibility of cracking when hardened, or low-alloy steels with a carbon equivalent of not over 0.20% maximum.
3. Low hardenability with high susceptibility of cracking when hardened, normally carbon manganese steels with less than 0.25% carbon and not over 1% manganese.
4. High-hardenable steels with low susceptibility of cracking when hardened. This includes most low-carbon low-alloy high-strength steels usually with carbon less than 0.15%, manganese up to 1.5%, nickel up to 1.5%, chromium 0.25%, molybdenum up to 0.25%, and vanadium up to 0.20%.
5. High-hardenable steels with high susceptibility of cracking when hardened. This would include alloy steels with carbon not exceeding 0.25% but with alloys.

There are several precautions that should be taken with the five classifications. They are as follows:

1. No extraordinary precautions required when welding thin-to-medium-thickness materials.
2. Use low-hydrogen processes and filler materials and utilize preheat for thick sections or increase heat input.
3. Low-hydrogen processes are recommended but not essential. High heat input should be used and preheat is not required except in thicker materials and should be in the range 480 to 660 °F (250 to 350 °C).
4. Low-hydrogen processes are required, preheat and interpass are suggested, high heat input processes are recommended, and preheat is increased as thickness increases.
5. Low-hydrogen processes are required, preheat and interpass temperature in the range 300 to 480 °F (150 to 250 °C) are necessary and a postweld heat treatment is required.

Recommended preheat and filler metals are given in the next chapter.

Weldability is extremely complex and all the welding factors interrelate. It is of vital importance for the success of welds to give consideration to all these factors.

QUESTIONS

15-1. What are some of the physical properties of a metal?

15-2. What are some of the mechanical properties of a metal?

15-3. What is ductility, and why is it important for welding?

15-4. Explain the different methods of measuring hardness. Is there a comparison?

15-5. What types of groups write metal specifications? What is the purpose of a specification?

15-6. How can you determine the metal composition if you know the specification number?

15-7. What are seven tests that can be made to identify a metal piece?

15-8. What can be determined by a metal's appearance?

15-9. Why is a magnet of value to help identify a piece of metal?

15-10. What is the spark test?

15-11. Why is it important to identify a metal before welding it?

15-12. What different ways is heat generated for welding?

15-13. What is the weld cooling rate and what importance is it to welding?

15-14. What is the major difference between welding metallurgy and casting metallurgy?

15-15. What are the three most common crystal structures of metals? Explain.

15-16. What is an equilibrium diagram?

15-17. What is the microstructure of a metal? Name some microstructures.

15-18. What is the HAZ? What causes it?

15-19. What is the carbon equivalent formula? How is it used?

15-20. What is weldability?

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16

Welding the Steels

OUTLINE

16-1 WELDING CARBON AND LOW-ALLOY STEELS

Low-carbon steels are considered to be steels with a maximum of 0.15% carbon. Mild steels are those that contain 0.15 to 0.29% carbon. Low-alloy steels are those having a maximum of 0.29% carbon and with their total metal alloy content not exceeding 2%. Different groups have slightly different composition limits.

All the electrodes described in AWS specification A5.1 are applicable to the mild steels. The E60XX and E70XX classes of electrodes provide sufficient strength to produce 100% weld joints in the steels. The yield strength of electrodes, in these classes, will overmatch the yield strength of the mild and low-alloy steels. The E60XX class should be used for steels having yield strengths below 50,000 psi (35 kg/mm^2) and the E70XX class should be used for welding steels having a yield strength below 60,000 psi (42kg/mm^2). Low-hydrogen electrodes should be used and preheat is suggested when welding heavier materials, or restrained joints. The electrode that provides the desired operational features should be selected. When welding the low-alloy steels the operational charateristic of electrodes are ignored and only low-hydrogen electrodes or procedures are used.

Filler metal should be selected on the basis of strength and composition of the weld deposit. For low-alloy steels this means that the electrode class would be E70XX or higher. The strength level of bare solid and flux-cored electrode wires is also contained in the classification number. Select the strength level to match or overmatch the base metal. The composition is described by the suffix letter in the filler metal classification. For covered electrodes the suffix is shown in Figure 16-1 along with the chemistry of the deposited metal. For low-alloy, bare solid, or flux-cored electrodes, see the appropriate specification. The suffix is used to match the composition of the base metal. Electrodes and wire are not available to match the composition of every base metal, but an effort should be made to come as close as possible. For GMAW use 98% argon–2% oxygen, or 75% argon–25% CO_2, for shielding. For FCAW use 75% argon–25% CO_2, or 100% CO_2 for shielding. This allows the selection of the electrode to match not only the mechanical properties of the base metal, but also to approximately match the composition of the base metal.

The only E80XX or higher-strength electrodes that do not have low-hydrogen coverings are the EXX10 type electrodes which are designed specifically for welding pipe. The deep penetrating characteristics of the cellulosic electrodes make them suitable for cross-country pipe welding. The theory and practice is that alloy steel pipe is relatively thin and it is welded with cellulosic electrodes at relatively high currents. In addition, each welding pass is very thin and the weld metal is aged for a considerable length of time prior to putting the pipeline into service. This allows for hydrogen, which might be absorbed, to escape from the metal and not adversely affect the service life of the pipeline.

The remainder of this section is related to specific types of steels and provides guidance in the selection of filler metal for joining them. For those steels that may not be specifically mentioned, it is possible to relate them to the chemistry of the deposited weld metal in order to establish the proper electrode class.

Low-Carbon (Mild) Steels

Low-carbon steels include those in the AISI series C-1008 to C-1025. Carbon ranges from 0.10 to 0.25%, manganese ranges from 0.25 to 1.5%, phosphorus is 0.40% maximum, and sulfur is 0.50% maximum. Steels in this range are most widely used for industrial fabrication and construction. These steels can be easily welded with any of the arc, gas, and resistance welding processes.

Medium-Carbon Steels

The medium-carbon steels include those in the AISI series C-1030 to C-1050. The composition is similar to low-carbon steels, except that the carbon ranges from 0.25 to 0.50% and the manganese from 0.60 to 1.65%. With higher carbon and manganese the low-hydrogen type electrodes are recommended, particularly in thicker sections. Preheating may be required and should range from 300 to 500°F (149 to 260°C). Postheating is often specified to relieve stress and help reduce hardness that may have been caused by rapid cooling. Medium-carbon steels are readily weldable provided the above precautions are observed. They can be welded with all of the processes mentioned above.

High-Carbon Steels

High-carbon steels include those in the AISI series from C-1050 to C-1095. The composition is similar to medium-carbon steels, except that carbons ranges from 0.50 to

FIGURE 16-1 Suffixes for low-alloy steel electrodes.

Suffix	C	Mn	Si	Ni	Cr	Mo	Va
A1	0.12	0.60 or 1.00*	0.40 or 0.80*	—	—	0.40-0.65	—
B1	0.12	0.90	0.60 or 0.80*	—	0.40-0.65	0.40-0.65	—
B2L	0.05	0.90	1.00	—	1.00-1.50	0.40-0.65	—
B2	0.12	0.90	0.60 or 0.80*	—	1.00-1.50	0.90-1.20	—
B3L	0.05	0.90	1.00	—	2.00-2.50	0.90-1.20	—
B3	0.12	0.90	0.60 or 0.80*	—	2.00-2.50	0.90-1.20	—
B4L	0.05	0.90	1.00	—	1.75-2.25	0.40-0.65	—
C1	0.12	1.20	0.60 or 0.80*	2.0-2.75	—	—	—
C2	0.12	1.20	0.60 or 0.80*	3.0-3.75	—	—	—
C3	0.12	0.40-1.10	0.80	0.80-1.10	0.15	0.35	0.05
D1	0.12	1.25-1.75	0.60 or 0.80*	—	—	0.25-0.45	—
D2	0.15	1.65-2.00	0.60 or 0.80*	—	—	0.25-0.45	—
G	—	1.00 Min.	0.80 Min.	0.50 min.	0.30 min.	0.20 min.	0.10 min.
M	0.10	0.60-2.25*	0.60 or 0.80*	1.4-2.25*	0.15-1.50*	0.25-0.55*	0.05

*Amount depends on electrode classification. Single values indicate max per AWS A5.5.

1.03% and manganese ranges from 0.30 to 1.00%. Special precautions must be taken when welding steels in these classes. The low-hydrogen process or electrodes must be employed and preheating of from 400 to 600 °F (204 to 316 °C) is necessary, especially when heavier sections are welded. A postheat treatment, either stress relieving or annealing, is usually specified. High-carbon steels can be welded with the same processes mentioned previously.

Low-Alloy High-Strength Steels

The low-alloy high-strength steels represent the bulk of the remaining steels in the AISI designation system. These steels are welded with the E80XX, E90XX, and E100XX class of covered welding electrodes. It is for these types of steels that the suffix to the electrode classification number is used. These steels include the low-manganese steels, the low-to-medium nickel steels, the low-nickel–chromium steels, the molybdenum steels, the chromium–molybdenum steels, the nickel–chromium–molybdenum steels, and the other groups. Not included as an alloy steel but part of the AISI series are the sulfur steels. These are the series designated by 11XX, sometimes known as free-machining steels. Sulfur is 0.08 to 0.33%. These steels are difficult to weld, because of the high sulfur content, which has a tendency to produce porosity in the weld and cracking. Low-hydrogen electrodes of the miminum-strength level should be used. Welding is tedious on these steels and their use should be avoided when welding is required.

Low-Nickel Steels

These include those in AISI series 2315, 2515, and 2517. Carbon ranges from 0.12 to 0.30%, manganese from 0.40 to 0.60%, silicon from 0.20 to 0.45% and nickel from 3.25 to 5.25%. If the carbon does not exceed 0.15% preheat is not necessary, except for extremely heavy sections. If the carbon exceeds 0.15% preheat of up to 500 °F (260 °C), depending on thickness, is required. On thin material, ¼ in. (6.4 mm) or less, preheating is unnecessary. Stress relieving after welding is advisable. The electrode suffix C-1 or C-2 would be used, depending on the level of nickel in the base material. The strength level would be matched to the base metal. In all cases, the low-hydrogen coating is used.

Low-Nickel Chrome Steels

Steels in this group include the AISI 3120, 3135, 3140, 3310, and 3316. In these steels, carbon ranges from 0.14 to 0.34%, manganese from 0.40 to 0.90%, silicon from 0.20 to 0.35%, nickel from 1.10 to 3.75% and chromium 0.55 to 0.75%. Thin sections of these steels in the lower carbon ranges can be welded without preheat. A preheat of 200 to 300 °F (93 to 149 °C) is necessary for carbon in the 0.20% range; for higher carbon a preheat of up to 600 °F (316 °C) should be used. The weldment must be stress relieved or annealed after welding. The E80XX or E90XX electrodes should be used with the C-1 or C-2 suffix. There is no electrode type that will exactly provide a nickel-chrome deposit the same as the base metal.

Low-Manganese Steels

Included in this group are the AISI type 1320, 1330, 1335, 1340, and 1345 designations. In these steels, the carbon ranges from 0.18 to 0.48%, manganese from 1.60 to 1.90%, and silicon from 0.20 to .035%. Preheat is not required at the low range of carbon and manganese. Preheat of 250 to 300 °F (121 to 149 °C) is desirable as the carbon approaches 0.25%, and mandatory at the higher range of manganese. Thicker sections should be preheated to double the above figure. A stress relief postheat treatment is recommended. The E80XX or E90XX electrodes with the A-1, D-1, or D-2 suffix should be used.

Low-Alloy Chromium Steels

Included in this group are the AISI type 5015 to 5160 and the electric furnace steels 50100, 51100, and 52100. In these steels carbon ranges from 0.12 to 1.10%, manganese from 0.30 to 1.00%, chromium from 0.20 to 1.60%, and silicon from 0.20 to 0.30%. When carbon is at the low end of the range, these steels can be welded without special precautions. As the carbon increases and as the chromium increases, high hardenability results and a preheat of as high as 750 °F (399 °C) will be required, particularly for heavy sections. The B suffix should be used. Match the suffix to the chromium content.

Welding procedure information is then determined by means of the carbon equivalent formula given in Chapter 15. The carbon equivalent should be calculated for the exact composition. When only a range of composition is known use the maximum values to be on the safe side. When the carbon equivalent is 0.40% or lower, the material is considered readily weldable. Above 0.40% special controls are required. In all cases, low-hydrogen processes should be used and preheat may also be required. When the carbon equivalent exceeds 0.60%, preheating is required if the thickness exceeds ¾ in (19.1 mm). When the carbon equivalent exceeds 0.90%, preheat is absolutely required to a relatively high temperature on all except the thinnest material. This provides the guidance for establishing welding procedures using covered electrodes. For all but the simple work, the procedure should be qualified according to one of the standard tests to determine whether it produces the quality of weld expected.

When using the submerged arc welding process, it

is also necessary to match the composition of the electrode with the composition of the base metal. A neutral flux that neither detracts nor adds elements to the weld metal should be used. In general, preheat can be reduced for submerged arc welding because of the higher heat input and slower cooling rates involved. To make sure that the submerged arc deposit is low hydrogen, the flux must be dry and the electrode and base metal must be clean.

When using the gas metal arc welding process, the electrode should be selected to match the base metal and the shielding gas should be selected to avoid excessive oxidation of the weld metal. Preheating with the gas metal arc welding process should be in the same order as with shielded metal arc welding since the heat input is similar.

When using the flux-cored arc welding process, the deposited weld metal produced by the flux-cored electrode should match the base metal being welded. Preheat requirements would be similar to gas metal welding.

When low-alloy high-strength steels are welded to lower-strength grades the electrode should be selected to match the strength of the lower-strength steel. The welding procedure, that is, preheat, heat input, and so on, should be suitable for the higher-strength steel.

Weathering Steels

Weathering steels are low-alloy steels that can be exposed to the weather without being painted. The steel protects itself by means of a dense oxide coating (patina) which forms naturally on the steel when it is exposed to the weather. This tight oxide coating reduces continuing corrosion. The corrosion resistance of weathering steels is four to six times that of normal structural carbon steels, and two to three times that of many of the low-alloy structural steels. The weathering steels are covered by the ASTM specification A242. These steels have a minimum yield strength of 50,000 psi (35 kg/mm²) with an ultimate tensile strength of 70,000 psi (49 kg/mm²). Two of the better known weathering steels are Corten and Mayari R.

The weathering steels can be welded by all the arc welding processes and by gas welding and resistance welding. To maintain the weather resistance characteristic of the steel, a special welding procedure should be employed. Use the E7018 class to within one layer of the top of the joint. The top layer should be made with an E7018-C1 electrode since the 2% nickel in the weld deposit will cause the weld metal to weather the same as the weathering steel. The C-1 suffix weld deposit should be used for the top layer of any multipass weld.

The same concept can be used for gas metal arc welding, flux-cored arc welding, or submerged arc welding. The normal electrode used for a 50,000-psi steel would be employed, but this last layer would include alloy to provide weathering resistance.

16-2 WELDING ALLOY STEELS

Steel is considered to be an alloy steel when the maximum of the range given for the content of alloying elements exceeds one or more of the following limits: manganese 1.65%, silicon 0.60%, copper 0.60%, or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels: aluminum, boron, chromium up to 3.99%, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect.[1]

Some of the steels mentioned in the preceding section fall within this range and are considered low-alloying steels. Many of the steels shown by the AISI steel classification system are also in the alloy range. If the chromium content exceeds 4%, it will be considered a stainless steel.

To weld alloy steels successfully four factors must be considered:

1. Always use a low-hydrogen welding procedure, process, and filler metal.
2. Select a filler metal that matches the strength level of the alloy steel.
3. Select a filler metal that comes close to matching the composition of the alloy steel.
4. Match the welding heat input requirement to the alloy steel and its thickness, and use the proper welding procdure.

The AWS filler metal specifications for covered electrodes,[2] bare solid electrode wire,[3] and flux-cored electrode wires[4] provide data to select filler metals that meet specific strength levels and provide the desired alloy composition.

The first one, two, or three digits of the electrode classification is the minimum tensile strength of the deposited weld metal. This is handled slightly differently in the three specifications. It provides the information necessary to select the strength level of the weld metal, which should meet or slightly overmatch the base metal.

All three specifications provide suffix letters that designate the chemical composition of the deposited weld metal. Unfortunately, the three specifications are not in exact agreement. In general, the suffix letters indicate the following chemistry:

Suffix Letter	Chemistry
A	Carbon–molybdenum steel
B	Chromium–molybdenum steel
C or NI	Nickel–steel
D	Manganese–molybdenum steel
NM	Nickel–molybdenum steel
G, K, M, and W	Other low-alloy steels

The suffix letters are sometimes followed by a number which indicates a specific chemical composition range. The suffix numbers are a starting point for selecting filler metals. Refer to the specification for exact chemical composition. This information allows you to select the composition of the filler metal. The heat input requirement is discussed with the alloy steel information.

Quenched and Tempered Constructional Steels

The quenched and tempered constructional steels were developed in the early 1950s. These steels offer a number of advantages which have made them extremely popular in weldments, where a high strength-to-weight ratio is important. The unique properties of these steels are obtained from their chemical composition plus a quenched and tempered heat treatment. These steels have extremely high strength, in the order of 100,000 psi (70 kg/mm²) yield strength, combined with good weldability. In addition, they possess good ductility, good notch toughness, good fatigue strength, and corrosion resistance. They can be welded successfully with relatively conventional welding procedures. Minimum preheat is used and for most applications the weldments are used in the as-welded condition.

ASTM Specifications A514 and A517 have been written to cover the quenched and tempered constructional steels produced by different steel manufacturers. The grades and compositions are shown in Figure 16-2. A different grade is given to each steel trade name. Several other ASTM specifications cover these types of steels, but the welding outlined here will apply to all when the composition is similar.

Steels of the same basic composition are also made into castings and forgings. These steels are water quenched by special techniques from a temperature of 1500 to 1600°F (816 to 871°C) and tempered at a temperature of from 1000 to 1110°F (538 to 593°C). This produces a microstructure of tempered, low-temperature transformation products which have an excellent combination of strength and toughness.

The shielded metal arc, the gas metal arc, the flux-cored arc, and the submerged arc welding process can all be used. The gas tungsten arc welding process can be used but is restricted to the thinner sections. The electroslag welding process is not recommended for these steels because the long time at high temperature softens the steel and destroys the heat treatment. It is essential to keep the process a low-hydrogen process. This means dry electrode coating, dry flux, dry gas, clean joint preparation, and so on.

When using the shielded metal arc welding process, electrodes of the E11018M or E12018M classification should be used.

With the gas metal arc welding process the electrode should be an AWS Class E 120C-G, which is a proprietory electrode wire designed for this class of steel. The

FIGURE 16-2 Popular quenched and tempered steels, grades and composition per ASTM A514/517.

		Composition Percent							
ASTM Grade	Proprietary Steels	C Max.	Mn	Si	Cr	Ni	Mo	Cu Min	Other
A	NAXTRA 100	0.15-0.21	0.80-1.10	0.40-0.80	0.50-0.80	–	0.18-0.28	–	0.035-P, 0.040-S
B	T-1 Type A	0.15-0.21	0.70-1.00	0.20-0.30	0.40-0.65	–	0.15-0.25	–	0.035-P, 0.040-S, 0.01-0.03-Ti, 0.03-0.08-Va
C	Jalloy S-100	0.10-0.20	1.01-1.50	0.15-0.30	–	–	0.20-0.30	–	0.035-P, 0.040-S
D	Armco SSS100A	0.13-0.20	0.40-0.70	0.20-0.35	0.85-1.20	–	0.20-0.25	0.20-0.40	0.035-P, 0.040-S, 0.04-0.10-Ti
E	Armco SSS100	0.12-0.20	0.40-0.70	0.20-0.35	1.40-2.00	–	0.40-0.60	0.20-0.40	0.035-P, 0.040-S 0.04-0.10-Ti
F	USS T-1	0.10-0.20	0.60-1.00	0.15-0.35	0.40-0.65	0.70-1.00	0.40-0.60	0.15-0.50	0.035-P, 0.040-S, 0.03-Va
G	PX-100	0.15-0.21	0.80-1.10	0.50-0.90	0.50-0.90	–	0.40-0.60	–	0.035-P, 0.040-S
H	T-1 Type B	0.12-0.21	0.95-1.30	0.20-0.30	0.40-0.65	0.30-0.70	0.20-0.30	–	0.035-P, 0.040-S, 0.03-0.08-Va
J	RQ 100A	0.12-0.21	0.45-0.70	0.20-0.35	–	–	0.50-0.65	–	0.035-P, 0.040-S
K	CHT-100	0.10-0.20	1.10-1.50	0.15-0.30	–	–	0.45-0.55	–	0.035-P, 0.040-S
L	Armco SSS100B	0.13-0.20	0.40-0.70	0.20-0.35	1.15-1.65	–	0.25-0.40	0.20-0.40	0.035-P, 0.040-S, 0.04-0.10-Ti
M	RQ-100B	0.12-0.21	0.45-0.70	0.20-0.35	–	1.20-1.50	0.45-0.60	–	0.035-P, 0.040-S
N	NAXTRA 100A								
P	RQC-100	0.12-0.20	0.45-0.70	0.20-0.35	0.85-1.20	1.20-1.50	0.45-0.60	–	0.035-P, 0.040-S

Boron of 0.0005 to 0.005 added to each grade.

shielding gas should be 98% argon–2% oxygen or 75% argon–25% CO_2. Pure carbon dioxide can also be used. The electrode wire composition should be approximately the same as the composition of the base metal.

When welding with the flux-cored process use one of the AWS E110 or E120 type with T-1 through 5 usability class and with K number appropriate to the brand steel being used. The T number will indicate what shielding gas should be used.

With the submerged arc welding process, a neutral type of flux should be used. The electrode wire should be of the same or approximately the same composition as the base metal.

The last factor is to maintain the proper heat input. The heat input depends on the material thickness, the preheat employed, and the interpass temperature. For 1-in.-thick plate a minimum preheat of 50 °F (10 °C) is normally used. When the thickness is increased, a preheat of 200 °F (93 °C) is recommended. Higher preheats may be required for restrained joints. The allowable heat input is based on the joules per inch of weld joint given by the standard formula. The maximum heat input for different thicknesses of the different grades of the ASTM A514/A517 steels is given in Figure 16-3. These are suggested maximum heat input limits and may vary from grade to grade or by different manufacturers. Consult the steel manufacturer's technical data to determine the recommended maximum heat input limit. When these heat inputs are exceeded, there will be a loss of strength of the weld joint. The toughness of the steel in the heat-affected zone is usually excellent and the hardness of the heat-affected zone is normally lower than the base metal or the deposited weld zone. Producers of the T-1 steel have developed a welding heat input calculator that relates the travel speed, welding current, and arc volts to the heat input in kilojoules per inch. This calculator provides maximum heat inputs for different preheat and interpass temperatures based on different thicknesses of steel. As the plate thickness increases and with lower preheat temperatures, the maximum heat units are unlimited.

The stringer bead technique is preferred. The use of a full weave reduces the travel speed and increases the heat input above the maximum limits. If weaving is used, it should be restricted to two electrode diameters. The base metal should not be allowed to become overheated. When back gouging is required, it should be done with the air carbon arc process or by grinding. The surface should be ground after air carbon arc gouging to provide a clean surface for welding. The oxyacetylene flame should not be used for back gouging.

FIGURE 16-3 Suggested maximum heat input limits in joules per inch.

Plate Thickness-in.	Perheat and Interpass Temperature °F 70	200	300	400
3/16	17,500	14,000	11,500	9,000
1/4	23,700	19,200	15,800	12,300
1/2	47,400	35,500	31,900	25,900
3/4	88,600	69,900	55,700	41,900
1	Any	110,000	86,000	65,600
1-1/4	Any	154,000	120,000	94,000

Note this applies to Grade F. Check suppliers of other grades for values.

Defects in welds made on quenched and tempered constructional steels are more serious than the same defect in mild or low-carbon steels. The weld surface should be smooth, with contours that are well blended into the pieces being joined. Each weld should be made so that there is good penetration into the previous weld and no undercut. Complete penetration is essential to utilize the full strength of the quenched and tempered steel.

Micro Alloyed Steels

The quenched and tempered steels just described give excellent service but have proven to be hydrogen sensitive, and for this reason preheating has been employed for welding. The Q and C steels have relatively large amounts of alloying elements, and require heat treatment in manufacturing. It was felt that if preheat could be reduced or eliminated in thicker sections, considerable savings would result. In addition, heat input restrictions could be relaxed or eliminated.

The steel industry has developed a new family of weldable steels that overcome these problems. They are known as HSLA steels, micro alloyed steel, clean steel, and so on, and are identified by the ASTM A710 or ASTM 736 specification.[5] They have excellent notch toughness and good weldability due to the very low carbon content, which is 0.08% carbon maximum. Grain refinement is attained by microalloying with 0.01 to 0.05% columbium, and small additions of copper (1 to 1.3%), nickel (0.7 to 1%), chromium (0.60 to 0.90%), and molybdenum (0.15 to 0.25%) are used to achieve high strength. Small amounts of nitrogen are used. Each manufacturer has a different composition. The chromium and molybdenum optimize the precipitation of the copper. The nickel prevents hot shortness brought on by the copper and improves toughness. Aluminum is used for deoxidizing and grain refining. This microalloyed steel is extremely weldable without expensive preheat and heat input restrictions. This is due primarily to the low carbon content, which ranges from 0.04 to 0.08% carbon. It is also less sensitive to hydrogen. These steels are becoming very popular. They are available from sheet metal thicknesses to heavy plate.

There are three different classes of this steel based on three different methods of heat treatment. Plates rolled followed by an aging treatment constitute one class; plates rolled, normalized, and aged are covered by the second class; and the third class covers plates that are rolled, quenched, and aged. There are numerous pro-

ducers, each with different composition and properties. The covered electrode used for welding this steel is the E10018-M1 or the E12018-M2.

For GMAW use the electrode wire matching the strength level and alloy content of the HSLA steel you are using.[6] The shielding gas can be 98% argon–2% O_2, 75% argon–25% CO_2, or CO_2. For FCAW the same applies.

Special welding precautions are not required. The weld will have strength equal to the base metal and will have good toughness properties.

High Nickel Steels

The 9% nickel steels are quenched and tempered but are considered separately because they are intended for different types of service. The 9% nickel steels were developed to provide high strength and extreme toughness at very low operating temperatures. The reason for developing the material was to provide a steel that could be used to build tanks and vessesls for containing liquefied natural gas. The temperature of liquefied natural gas is -262 °F (-160 °C). The 9% nickel steel will provide good notch toughness at temperatures down to -320 °F (-196 °C). There is also a low-nickel steel in the 5% range, plus 0.25% molybdenum, which will provide good properties at temperatures as low as -275 °F (-170 °C). These steels are welded in the heat-treated condition and do not require a postweld heat treatment to obtain welds that provide properties essentially equal to the base metal.

The 9% nickel steel is supplied in the heat-treated condition. It is specified by ASTM A353 and A553. Two types of heat treatments may be used. One is known as the "double normalized and tempered condition" and the other is accomplished by normalizing at 1650 °F (900 °C), then normalizing at 1450 °F (790 °C) followed by a tempering at 1050 °F (570 °C). In the second way the steel furnished is water quenched and tempered with water quenching at 1470 °F (800 °C) and then tempering at 1050 °F (570 °C). The toughness of this steel is obtained by the small amount of austenite, which is reformed during the tempering treatment. This phase is stable at the subzero temperatures and contributes to the toughness of the steel.

The 9% nickel steel can be flame cut using normal oxygen fuel gas equipment. The cutting speed is slower than on mild steel. Flame-cut surfaces should be ground to remove any hardened metal and the oxide surface. Welding is done in the fully heat-treated condition and the heat-affected zone has a somewhat different microstructure than the base metal. Welding can be accomplished by shielded metal arc welding, submerged arc welding, gas metal arc welding, and flux cored arc welding.

When the shielded metal arc welding process is used, the high nickel–chrome–iron electrodes are used. These are the AWS ENiCrFe-2 type and ENiCrFe-3 type. The higher nickel-chrome electrode will produce slightly higher strength welds which will match the base metal. A preheat or postheat is not required on material 2 in. (50 mm) thick or less. Before welding the base metal should be brought up to normal room temperature of 70 °F (21 °C). When making V- or bevel groove welds the minimum included angle should be 70°. The high-nickel electrodes operate differently from mild or stainless steel electrodes. They have low penetration and do not flow or wash into the sidewall of the weld joint. The electrode should be pointed to place the deposited metal where it is desired.

When using submerged arc welding, the same basic analysis of electrode wire is used with a neutral-type welding flux. For thinner materials, a room-temperature preheat of 70 °F (21 °C) is used. When welding material 2 in. (50 mm) and thicker, a preheat of 250 to 300 °F (121 to 149 °C) is recommended. The same temperature is used for the interpass temperature.

When using gas metal arc welding, the high-nickel–chrome electrode, AWS type ERNiCrFe-6, is used and a shielding gas of 90% helium and 10% argon is recommended. Short-circuiting transfer is used and the properties of the weld are essentially the same as the base metal. The pulsed mode of GMAW is widely used for welding 9% nickel steel. When using flux-cored arc welding, special proprietory electrode wires are used.

Chromium–Molybdenum Steels

The chromium–molybdenum steels (sometimes called chrome-moly) were developed for elevated-temperature service. They have been used extensively in power piping, where they operate at high pressures and temperatures between 700 and 1100 °F (371 to 599 °C). Popular Cr-Mo steels are shown in Figure 16-4.

The major reason for using chrome-moly steels is that they maintain their strength at high temperatures. They do not creep, which means that they do not stretch or deform under long periods of use at high pressures and temperatures. Also, they do not become brittle after extended periods of high-temperature service. Carbon steels, on the other hand, do tend to stretch at high-temperature service and will become brittle in time.

The chrome-moly steels are used in the normalized and tempered condition and in the quenched and tempered condition. The type of heat treatment dictates the strength level of the steel. The strength levels extend from 85,000 psi (59 kg/mm²) to 135,000 psi (94 kg/mm²). There are a number of compositions that have become popular. These are the 1% Cr–½% Mo, 1¼% Cr–½% Mo, the 2% Cr–½% Mo, the 2¼% Cr–1% Mo, and the 5% Cr–½% Mo.

Shielded metal arc welding, gas tungsten arc welding, and gas metal arc welding are widely used for joining the chrome-moly steels. Submerged arc welding

Popular Name	C	Mn	Si	Cr	Mo	Recommended Electrode Suffix
1/2 Cr-1/2 Mo	0.10 to 0.20	0.30 to 0.60	0.10 to 0.30	0.50 to 0.81	0.44 to 0.65	B1
1 Cr-1/2 Mo	0.15 max.	0.30 to 0.60	0.50 max.	0.80 to 1.25	0.44 to 0.65	B2L
1-1/4 Cr-1/2 Mo	0.15 max.	0.30 to 0.60	0.50 to 1.00	1.0 to 1.50	0.44 to 0.65	B2L
2 Cr-1/2 Mo	0.15 max.	0.30 to 0.60	0.50 max.	1.65 to 2.35	0.44 to 0.65	B4L
2-1/4 Cr-1 Mo	0.15 max.	0.30 to 0.60	0.50 max.	1.90 to 2.60	0.87 to 1.13	B3

From ASTM A199 and A333.

FIGURE 16-4 Composition of popular chrome-molybdenum steels.

and flux-cored arc welding are also used. It is necessary to match the weld metal deposit analysis closely with the composition of the base metal.

For shielded metal arc welding, the electrode class suffix ranging from B1 with ½% chrome-½% moly up through the B4 for the 2½% chrome-½% moly identifies the composition. The higher levels of chromium are not specified by means of a suffix system. Proprietory electrodes are available for the higher chrome-moly steels.

The AWS specifications for chrome-moly bare solid and flux-cored electrodes go up to the 2½% chrome-1% moly analysis. Above this proprietory electrodes are available that match many compositons.

- For GTAW use argon for shielding.
- For GMAW use CO_2 or argon-CO_2 mixture for shielding.
- For FCAW use CO_2 or argon-CO_2 mixture for shielding.

Much of the welding on these steels is done on pipe. For pipe welding, the gas tungsten arc welding process is often used for making the root pass. The shielded metal arc welding process, gas metal arc, or flux-cored arc welding can be used for the remainder of the weld joint. The submerged arc welding process would be used for roll welding of pipe subassemblies.

The chrome-moly steels are hardenable steels; therefore, it is necessary to provide a welding procedure that includes preheating and postheating. Preheat temperatures range from a minimum of 100°F(37.8°C) to as high as 700°F (371°C). The preheat temperature is dependent on the carbon content and the thickness of the material being welded. If the carbon content is below 0.20% and the thickness is less than ⅜ in. (9.5 mm), the minimum 100°F preheat can be used. However, if carbon is above this figure and the wall thickness is greater, the temperature should be increased to 200°F and up to 400°F. For the higher chrome-molys and thicker sections, the preheat will extend up to 700°F (371°C); however, if thickness is less than ¾ in. (19 mm), the preheat can be reduced to half this value. Details of welding procedures for welding piping is given by the AWS "Recommended Practice for Welding of Chromium-Molybdenum Steel Piping and Tubing."[7] Specific preheat values are given for different types and wall thicknesses of chrome-moly pipe.

Shielded metal arc welding electrodes for chrome-moly steels are always of the low-hydrogen type. Low-hydrogen electrodes are difficult to use with open root joints; therefore, the gas tungsten arc welding process is used for making the root pass. Backup rings are not used for welding high-pressure, high-temperature steam pipe.

A postheat treatment is required when the carbon content exceeds 0.20% or the wall thickness is over ½ in. (12 mm). The heat treatment temperature is from 1150 to 1300°F (621 to 704°C). The lower temperatures are used with the thinner material and the higher temperatures for the heavier wall thickness. Specific recommendations are provided in the above-mentioned AWS booklet.

Where different grades of chrome-moly steels are welded together, the preheat and postheat temperatures should be based on the higher-alloy material, but the welding electrode can be based on the lower-alloy material.

Steel Castings

The welding of steel castings is important since they are often incorporated into weldments. Steel castings may have foundry defects which are repaired by welding. Steel castings are made in many different analyses, and it is necessary to know the composition of the casting in order to select the proper filler metal. Castings are easily identifiable since they carry an imprint of the foundry where they are made. By checking with the foundry it is possible to determine the exact analysis of the casting.

In general, steel castings have higher amounts of carbon than rolled steel. Many steel castings are heat treated to obtain desired properties. When welding heat-treated castings one of the problem areas is that the weld metal deposit usually has a lower carbon content than the casting, and the heat treatment may not produce the same mechanical properties in the weld metal as in the casting. It is best to overmatch the analysis of the weld deposit over the composition of the casting. This will tend

to produce a hardness level in the weld metal similar to that in the casting.

When using gas metal arc, flux-cored arc, or submerged arc welding, this problem is reduced because of the higher penetration of these processes. There is more dilution of the weld metal from the base metal, and a higher carbon deposit will result. This provides a weld metal deposit more similar to the casting and will provide comparable heat-treated properties.

The flux-cored arc welding process is extremely popular for weld repairing castings. Flux-cored electrode wires are now available with weld metal deposits matching many steel casting compositions.

Welding procedures for castings should be developed based on the casting analysis. All other factors concerning weldability must be considered in developing the procedure, including preheat, heat input, and postheat requirements.

16-3 WELDING STAINLESS STEELS

Stainless steels, or, more precisely, corrosion-resisting steels are a family of iron-base alloys having excellent resistance to corrosion. These steels do not rust and strongly resist attack by a great many liquids, gases, and chemicals. Many of the stainless steels have good low-temperature toughness and ductility. Most stainless steels exhibit good strength properties and resistance to scaling at high temperatures. All stainless steels contain iron as the main element and chromium in amounts ranging from about 11 to 30%. Chromium provides the basic corrosion resistance to stainless steels. A thin film of chromium oxide forms on the surface of the metal when it is exposed to the oxygen of the air. This film acts as a barrier to further oxidation, rust, and corrosion. Steels which contain only chromium or chromium with small amounts of other alloys are known as straight chrome types. There are about 15 types of straight chrome stainless steels. The straight chrome steels are the 400 series of stainless steels, which are highly magnetic.

Nickel is added to certain of the stainless steels, which are known as *chrome–nickel* stainless steel. The addition of nickel reduces the thermal conductivity and decreases the electrical conductivity. The chrome–nickel steels are in the 300 series of stainless steels. They have austenitic microstructure and are nonmagnetic.

The chrome–nickel stainless steels contain small amounts of carbon. Carbon is undesirable particularly in the 18% chrome–8% nickel group. Carbon will combine with chromium to form chromium carbides which do not have corrosion resistance. Chromium carbides are formed when the steel is held in the temperature range of 800 to 1600 °F (427 to 871 °C) for prolonged periods, which can happen during welding with slow cooling. The chemical reaction of carbon with chromium to form chromium carbide is called *carbide precipitation*. Carbon can be controlled, however, by the use of stabilizing elements. Carbide precipitation can be reduced or prevented in two ways. The first way is to keep the carbon level at 0.03% or less, which eliminates the formation of chromium carbides. Stainless steels with low carbon in this range are commonly referred to as ELC (extra low carbon) types. The other way of preventing carbide precipitation is to use a stabilizing element. The most popular stabilizers are titanium and columbium (niobium). These elements will combine with carbon to form titanium or columbium carbides, which have corrosion resistance. Both types of stainless steels have equivalent corrosion resistance. These types of stainless steels are identified as ELC type or stabilized type.

Manganese is added to some of the chrome-nickel alloys. Usually these steels contain slightly less nickel since the chrome–nickel–manganese alloys were developed originally to conserve nickel. In these alloys, a small portion of the nickel is replaced by the manganese, generally in a 2:1 relationship. The 200 series of stainless steels are the chrome–nickel–manganese series. These steels have an austenitic microstructure and are nonmagnetic. The 201 and 202 types are used as alternates for 301 and 302.

Molybdenum is also included in some stainless steel alloys. Molybdenum is added to improve the creep resistance of the steel at elevated temperatures. It will also increase resistance to pitting and corrosion in many applications. The different alloy groupings are shown in Figure 16-5.

FIGURE 16-5 Groups of stainless steels.

Series Designation	Metallurgical Group	Principle Elements	Hardenable By Heat Treatment	Magnetic
2xx	Austenitic	Chromium-nickel-manganese	Non-hardenable**	Nonmagnetic
3xx	Austenitic	Chromium-nickel steels	Non-hardenable	Nonmagnetic
4xx	Martensitic	Chromium steels	Hardenable	Magnetic
4xx	Ferritic	Chromium steels	Non-hardenable	Magnetic
5xx*	Martensitic	Chromium-molybdenum steels	Martensitic	Magnetic

*Not stainless.
**Will work harden.

Stainless steels are sometimes identified by numbers which refer to the principal alloying elements, such as 18/8, 25/20, and so on. This identification system has been supplanted by the American Iron and Steel Institute system, which utilizes a three-digit number (Figure 16-6). The first digit indicates the group and the last two digits indicate specific alloys. The AISI numbers refer to the alloys as chrome-nickel stainless steels and chromium stainless steels. They are, however, also identified according to their microstructure which can be austenitic, martensitic, or ferritic. The austenitic chrome-nickel-manganese (200 series) and austenitic chrome-nickel (300 series) steels are shown in the upper portion of the table. The martensitic types are shown in the center part of the table and represent a portion of the 400 series; the ferritic types are shown in the lower portion of the table and are the remaining alloys in the 400 series. The duplex stainless steels are covered later.

FIGURE 16-6 AISI stainless steel classification system. (Courtesy of the American Iron and Steel Institute.)

AISI No.	Chemical Analyses of Stainless Steels (Percent)					
	Carbon	Manganese	Silicon	Chromium	Nickel	Other Elements
Chromium-nickel-magnesium-austenitic—nonhardenable						
201	0.15 max.	5.5/7.5	1.0	16.0/18.0	3.5/5.5	$N_2$0.25 max
202	0.15 max.	7.5/10.	1.0	17.0/19.0	4.0/6.0	$N_2$0.25 max.
Chromium-nickel-austenitic—nonhardenable						
301	0.15 max.	2.0	1.0	16.0/18,0	6.0/8.0	
302	0.15 max.	2.0	1.0	17.0/19.0	8.0/10.0	
302B	0.15 max.	2.0	2.0/3.0	17.0/19.0	8.0/10.0	—
303	0.15 max.	2.0	1.0	17.0/19.0	8.0/10.0	S 0.15 min
303Se	0.15 max.	2.0	1.0	17.0/19.0	8.0/10.0	Se 0.15 min.
304	0.08 max.	2.0	1.0	18.0/20.0	8.0/12.0	
304L	0.03 max.	2.0	1.0	18.0/20.0	8.0/12.0	—
305	0.12 max.	2.0	1.0	17.0/19.0	10.0/13.0	—
308	0.08 max.	2.0	1.0	19.0/21.0	10.0/12.0	—
309	0.20 max.	2.0	1.0	22.0/24.0	12.0/15.0	—
309S	0.08 max.	2.0	1.0	22.0/24.0	12.0/15.0	—
310	0.25 max.	2.0	1.50	24.0/26.0	19.0/22.0	—
310S	0.08 max.	2.0	1.50	24.0/26.0	19.0/22.0	—
314	0.25 max.	2.0	1.5/3.0	23.0/26.0	19.0/22.0	—
316	0.08 max.	2.0	1.0	16.0/18.0	10.0/14.0	Mo 2.0/3.0
316L	0.03 max.	2.0	1.0	16.0/18.0	10.0/14.0	Mo 2.0/3.0
317	0.08 max.	2.0	1.0	18.0/20.0	11.0/15.0	Mo 3.0/4.0
321	0.08 max.	2.0	1.0	17.0/19.0	9.0/12.0	Ti 5 X C min.
347	0.08 max.	2.0	1.0	17.0/19.0	9.0/13.0	Cb + Ta10 × C min.
348	0.08 max.	2.0	1.0	17.0/19.0	9.0/13.0	Ta 0.10 max.
Chromium-martensitic—hardenable						
403	0.15 max.	1.0	0.5	11.5/13.0	—	—
410	0.15 max.	1.0	1.0	11.5/13.5	—	—
414	0.15 max.	1.0	1.0	11.5/13.5	1.25/2.5	—
416	0.15 max.	1.25	1.0	12.0/14.0	—	S 0.15 min.
416Se	0.15 max.	1.25	1.0	12.0/14.0	—	Se 0.15 min.
420	Over 0.15	1.0	1.0	12.0/14.0	—	—
431	0.20 max.	1.0	1.0	15.0/17.0	1.25/2.5	—
440A	0.60/0.85	1.0	1.0	16.0/18.0	—	Mo 0.75 max.
440B	0.75/0.95	1.0	1.0	16.0/18.0	—	Mo 0.75 max.
440C	0.95/1.2	1.0	1.0	16.0/18.0	—	Mo 0.75 max.
Chromium-ferritic—nonhardenable						
405	0.08 max.	1.0	1.0	11.5/14.5	—	A1 1.1/0.3
430	0.12 max.	1.0	1.0	14.0/18.0	—	—
430F	0.12 max.	1.25	1.0	14.0/18.0	—	S 0.15 min.
430Se	0.12 max.	1.25	1.0	14.0/18.0	—	Se 0.15 min.
446	0.20 max.	1.50	1.0	23.0/27.0	—	N 0.25 max.
Martensitic						
501	Over 0.10	1.0	1.0	4.0/6.0	—	Mo 0.40/0.65
502	0.10 max.	1.0	1.0	4.0/6.0	—	Mo 0.40/0.65

The three most popular processes for welding stainless steels are shielded metal arc, gas tungsten arc, and gas metal arc welding; however, almost all the welding processes can be used.

Stainless steels are slightly more difficult to weld than mild carbon steels. The physical properties of stainless steel are different from mild steel and this makes it weld differently. These differences are:

1. Lower melting temperature
2. Lower coefficient of thermal conductivity
3. Higher coefficient of thermal expansion
4. Higher electrical resistance

The properties are not the same for all stainless steels, but they are the same for those having the same microstructure. In view of this, stainless steels of the same metallurgical class have similar welding characteristics and are grouped according to the metallurgical structure with respect to welding.

Austenitic Types

The austenitic stainless steels have about 45% higher manganese, are not hardenable by heat treatment and are nonmagnetic in the annealed condition. They may become slightly magnetic when cold worked or welded. This helps identify this class of stainless steels. All the austenitic stainless steels are weldable with most of the welding processes, with the exception of type 303, which contains high sulfur, and type 303Se, which contains selenium to improve machinability.

The austenitic stainless steels have about 45% higher thermal coefficient of expansion, higher electrical resistance, and lower thermal conductivity than mild-carbon steels. High travel speed welding is recommended, which will reduce heat input, reduce carbide precipitation, and minimize distortion. The melting point of austenitic stainless steel is slightly lower than mild-carbon steel. Because of lower melting temperature and lower thermal conductivity welding current is usually lower. The higher thermal expansion dictates that special precautions should be taken with regard to warpage and distortion. Tack welds should be twice as often as normal. Any of the distortion reducing techniques such as back-step welding, skip welding, and wandering sequence should be used. On thin materials it is very difficult to completely avoid buckling and distortion.

Ferritic Stainless Steels

The ferritic stainless steels are not hardenable by heat treatment and are magnetic. All the ferritic types are considered weldable with the majority of the welding processes except for the free-machining grade of 430F, which contains high sulfur. The coefficient of thermal expansion is lower than the austenitic types and is about the same as mild steel. Welding processes that tend to increase carbon pickup are not recommended. This would include the oxyfuel gas process, carbon arc process, and gas metal arc welding with CO_2 shielding gas. The ferritic steels in the 400 series have a tendency for grain growth at elevated temperatures. Grain growth occurs at about 1600°F (871°C) and increases rapidly at higher temperatures. The lower chromium types show tendencies toward hardening with a resulting martensitic type structure at grain boundaries of the weld area. This lowers the ductility, toughness, and corrosion resistance at the weld. For heavier sections a preheat of 400°F (204°C) is beneficial. To restore full corrosion resistance and improve ductility after welding, annealing at 1400 to 1500°F (760 to 816°C), followed by a water or air quench, is recommended. Large grain size will still prevail, however, and toughness may be impaired. Toughness can be improved only by cold working such as peening the weld. If heat treating after welding is not possible and service demands impact resistance, an austenitic stainless steel filler metal should be used. Otherwise, the filler metal is selected to match the base metal.

Martensitic Stainless Steels

The martensitic stainless steels are hardenable by heat treatment and are magnetic. The low-carbon types can be welded without special precautions. The types with over 0.15% carbon tend to be air hardenable and, therefore, preheat and postheat of weldments are required. A preheat temperature range of 450 to 550°F (232 to 288°C) is recommended. Postheating should immediately follow welding and be in the range 1200 to 1400°F (649 to 760°C), followed by slow cooling.

If preheat and postheat are not possible, an austenitic stainless steel filler metal should be used. Type 416Se is the free-machining composition and should not be welded. Welding processes that tend to increase carbon pickup are not recommended. Increased carbon content increases crack sensitivity in the weld area.

Duplex Stainless Steels

A new class of stainless steels has been developed which combines the best properties of austenitic and ferritic stainless steels. They combine the ductility and corrosion resistance of the austenitic types and the strength and resistance to corrosion cracking of the ferritic types. The name *duplex* indicates that their characteristic micro structure is typically 50% ferrite and 50% austenite. This is done by the adjustment of the chromium and nickel contents and by the addition of nitrogen or copper to stabilize the austenite. The duplex stainless steels are widely utilized by the petrochemical, pulp and paper, and oil and gas industries. One of the major uses is for pipe and

tubing systems. This is to provide better corrosion resistance to sulfuric acid corrosion and better resistance to pitting in seawater, and to provide good resistance to stress corrosion cracking in these types of environments.

There are three basic classes based on the percent chromium: the 18%, 22%, and 25% chromium-containing alloys (see ASTM A789 for chemical requirements). Some are nitrogen containing, which improves mechanical properties and provides better resistance to general corrosion and pitting. Some contain small amounts of copper, which promotes better corrosion resistance in polluted seawater, and improved resistance to sulfuric acid corrosion, as well as high mechanical properties. The duplex alloys also have a much lower carbon level than regular stainless steel compositions. The duplex stainless steels are susceptible to embrittlement if used for prolonged periods at elevated temperatures.

The physical and mechanical properties of the duplex stainless steels affect welding. The yield strength is typically about double that of type 316L, and the tensile properties are considerably higher than standard austenitic grades. The thermal conductivity of duplex stainless is approximately half that of carbon steels, but about 25% more than most austenitic stainless steels. The coefficient of thermal expansion of the duplex stainless steel is approximately the same as carbon steel, and about 40% less than that of the austenitic stainless steels. Duplex stainless steels are magnetic. Because of these factors, duplex stainless steels are easier to weld than austenitic stainless steels.

The normal arc welding processes, shielded metal arc, gas tungsten arc, gas metal arc, plasma arc, and submerged arc welding can all be used. In addition, electron beam and laser welding are used as well as resistance welding. The joint details can be the same as those employed for austenitic stainless steels. The welding parameters would be essentially the same. Preheat should not be used and the interpass temperature should not exceed 300 °F (150 °C). Heat input should be on the low side. Surface cleanliness is a must when welding duplex stainless steels. It is necessary to eliminate any source of hydrogen in the welding operation. For the gas-shielded processes, particularly on pipe, argon purge gas should be used.

The filler metals to be used for welding duplex stainless steels should match the base metal composition. Filler metal and electrodes are available to match each of the three grades. Normally, there is no need for a postweld heat treatment. It is essential that thorough cleaning, chemical or mechanical, be used after welding.

The selection of the filler metal alloy for welding the stainless steels is based on the composition of the stainless steel. The various stainless steel filler metal alloys (Figure 16-7) are normally available as covered electrodes and as bare solid wires. Flux-cored electrode wires are available for welding some stainless steels.

Figure 16-8 gives the recommended filler metal alloy for welding the various stainless steel base metals. The table also shows some alternate alloys. Alternates are provided since there are so many different stainless steel types and there are not electrodes of each type. It is possible to weld several different stainless base metals with the same filler metal alloy.

For shielded metal arc welding, there are two types of electrode coatings. These are the lime type indicated by the suffix 15 and titania type designated by the suffix 16. The lime type electrodes are used only with direct cur-

FIGURE 16-7 Stainless steel filler metal alloys. (From Ref. 8.)

AWS Class	Typical Composition %						
	C	Cr	Ni	Mo	Mn	Si	Others
E308	0.08	19.5	10.5	—	2.5	0.90	—
E308L	0.04	19.5	10.5	—	2.5	0.90	—
E309	0.15	23.5	13.5	—	2.5	0.90	—
E309Cb	0.12	23.5	13.5	—	2.5	0.90	Cb + Ti —0.85
E309Mo	0.12	23.5	13.5	2.5	2.5	0.90	—
E310	0.20	26.5	21.5	—	2.5	0.75	—
E310Cb	0.12	26.5	21.5	—	2.5	0.75	Cb + Ti —0.85
E310Mo	0.12	26.5	21.5	2.5	2.5	0.75	—
E312	0.15	30.0	9.0	—	2.5	0.90	—
E316	0.08	18.5	12.5	2.5	2.5	0.90	—
E316L	0.04	18.5	12.5	2.5	2.5	0.90	—
E317	0.08	19.5	13.0	3.5	2.5	0.90	—
E318	0.08	18.5	12.5	2.5	2.5	0.90	—
E320	0.07	20.0	34.0	2.5	2.5	0.60	—
E330	0.25	15.5	35.0	—	2.5	0.90	—
E347	0.08	19.5	10.0	—	2.5	0.90	—
E410	0.12	12.5	0.60	—	1.0	0.90	—
E430	0.10	16.5	0.60	—	1.0	0.90	—

Note: Remainder is iron.

	AISI No.	Recommended Filler Metal 1st Choice	2nd Choice	Popular Name	Remarks
Cr-Ni-Mn	201	308	308L		Substitute for 301
	202	308	308L		Substitute for 302
Cr-Ni-Austenitic	301	308	308L		
	302	308	308L		
	302B	308	309		High Silicon
	303	–	–		Free machining–welding not recommended–312
	303Se	–	–		Free machining–welding not recommended–312
	304	308	308L	18/8	
	304L	308L	347	18/8 Elc	Extra low carbon
	305	308	–		
	308	308	–	19/9	
	309	309	–	25/12	
	309S	309	–		Low carbon
	310	310	–	25/20	
	310S	310	–		Low carbon
	314	310	–		
	316	316	309Cb	18/12Mo	
	316L	316L	309Cb	18/12 Elc	Extra low carbon
	317	317	309Cb	19/14Mo	
	321	347	308L		
	347	347	308L	19/9 Cb	Difficult to weld in heavy sections
	348	347	–	19/9CbLTa	
Cr-Martensitic	403	410	–		
	410	410	430	12Cr	
	414	410	–		
	416	410	–		Use 410-15
	416Se	–	–		Free machining welding not recommended
	420	410	–	12 Cr Hc	High Carbon
	431	430	–		
	440A	–	–		High carbon—welding not recommended
	440B	–	–		High carbon—welding not recommended
	440C	–	–		High carbon—welding not recommended
Cr-Ferritic	405	410	405Cb		
	430	430	309	16Cr	
	430F	–	–		Free machining—welding not recommended
	430FSe	–	–		Free machining—welding not recommended
	446	309	310		
	501	502	–	5Cr-1/2Mo	Chrome-moly steel
	502	502	–	5Cr-1/2Mo	Chrome-moly steel

FIGURE 16-8 Recommended filler metals for stainless steels (use E or R prefix).

rent electrode positive (reverse polarity). The titania-coated electrode with the suffix 16 can be used with alternating current and with direct current electrode positive. Both coatings are of the low-hydrogen type and both are used in all positions; however, the 16 type is smoother, has more welder appeal, and operates better in the flat position. The lime-type electrodes are more crack resistant and are slightly better for out-of-position welding. The procedure schedule for using the shielded metal arc welding process is given in Figure 16-9. The width of weaving should be limited to 2½ times the diameter of the electrode core wire.

Covered electrodes for shielded metal arc welding must be stored at normal room temperatures in dry areas. These electrode coatings, of low hydrogen type, are susceptible to moisture pickup. Once the electrode box has been opened, the electrodes should be kept in a dry box until used. If the electrodes do become exposed to moisture they should be reconditioned in accordance with procedures that were presented in Chapter 13.

The gas tungsten arc welding process is widely used for thinner sections of stainless steel. The 2% thoriated tungsten is recommended and the electrode should be ground to a taper. Argon is normally used for gas shielding; however, argon-helium mixtures are sometimes used for automatic applications. Figure 16-10 shows the

FIGURE 16-9 Welding procedure schedule for SMAW of stainless steel.

	Material Thickness		Electrode	WELDING CURRENT DECP		
ga	fraction	in.	Dia in.	Flat	Vertical	Overhead
26	—	0.018	5/64	20-35	20-25	20-30
22	—	0.030	5/64	30-45	30-40	30-40
18	—	0.048	3/32	50-70	40-55	50-60
14	—	0.075	3/32	60-90	50-65	60-95
11	—	0.120	1/8	90-120	75-90	90-110
—	3/16	0.188	5/32	120-150	90-110	120-140
—	1/4	0.250	3/16	150-200	100-125	—

FIGURE 16-10 Welding procedure schedule for GTAW of stainless steel.

Material Thickness (or Fillet Size)			Type of Weld	Tungsten Electrode Diameter		Filler Rod Diameter		Nozzle Size Inside Dia.	Shielding Gas Flow	Welding Current Amps	No. of	Travel Speed (per pass)
ga	in.	mm	Fillet or Groove	in.	mm	in.	mm	in.	cfh	DCEN	Passes	ipm
24			Square Groove	0.040	1.0	1/16	1.6	1/4	10	20-50	1	26
18			Square Groove	1/16	1.6	1/16	1.6	1/4	10	50-80	1	22
1/16	0.062	1.6	Square Groove	1/16	1.6	1/16	1.6	1/4	12	65-105	1	12
1/16	0.062	1.6	Fillet	1/16	1.6	1/16	1.6	1/4	12	75-125	1	10
3/32	0.093	2.4	Square Groove	1/16	1.6	3/32	2.4	1/4	12	85-125	1	12
3/32	0.093	2.4	Fillet	1/16	1.6	3/32	2.4	1/4	12	95-135	1	10
1/8	0.125	3.2	Square Groove	1/16	1.6	3/32	2.4	5/16	15	100-135	1	12
1/8	0.125	3.2	Fillet	1/16	1.6	3/32	2.4	5/16	15	115-145	1	10
3/16	0.188	4.8	Square Groove	3/32	2.4	1/8	3.2	5/16	15	150-225	1	10
3/16	0.188	4.8	Fillet	1/8	3.2	1/8	3.2	3/8	18	175-250	1	8
1/4	0.25	6.4	Vee Groove	1/8	3.2	3/16	4.8	3/8	18	225-300	2	10
1/4	0.25	6.4	Fillet	1/8	3.2	3/16	4.8	3/8	18	225-300	2	10
3/8	0.375	9.5	Vee Groove	3/16	4.8	3/16	4.8	1/2	25	220-350	2-3	10
3/8	0.379	9.5	Fillet	3/16	4.8	3/16	4.8	1/2	25	250-350	3	10
1/2	0.50	12.7	Vee Groove	3/16	4.8	1/4	6.4	1/2	25	250-350	3	10
1/2	0.50	12.7	Fillet	3/16	4.8	1/4	6.4	1/2	25	250-350	3	10

1 - Increase amperage when backup is used.

2 - Data is for flat position. Reduce amperage 10% to 20% when welding is horizontal, vertical, or overhead position.

3 - For tungsten electrodes—1st choice 2% thoriated EWTh2; 2nd choice 1% thoriated EWTh1.

4 - Argon is used for shielding. The 75% helium 25% argon mixture is used for heavier thickness.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Electrode Diameter in.	mm	WELDING POWER Current Amps DC	Arc Volt EP	Wire Feed Speed ipm	Shielding Gas Flow cfh	No. of Passes	Travel Speed (per pass) ipm
16	0.063	1.6	Sq. groove & fillet	0.035	0.9	60-100	15-18	90-190	12-15	1	15-30
13	0.093	2.4	Sq. groove & fillet	0.035	0.9	125-150	18-21	230-280	12-15	1	20-30
				0.045	1.1	125-150	18-21	130-160			20-30
11	0.125	3.2	Sq. groove & fillet	0.035	0.9	130-160	19-24	250-280	12-15	1	20-25
				0.045	1.1	150-225	19-24	160-260			20-30
5/32	0.156	3.9	Vee groove & fillet	0.045	1.1	190-250	22-26	200-290	15-20	1	25-30
1/4	0.250	6.4	Vee groove & fillet	0.045	1.1	225-300	24-30	260-370	25-30	2	25-30

Data is for flat position. Reduce current 10-20% for other positions.

Gas selection—Argon-oxygen (1 to 2% oxygen + argon)—flat position and horizontal fillets.
Argon-CO_2 (75% Argon-25% CO_2)—all position, some carbon pickup.
Helium-argon-CO_2 (90%-7.5%-2.5%)—for all position welding.
Carbon dioxide (CO_2)—where carbon pickup can be tolerated.

FIGURE 16-11 Welding procedure schedule for GMAW of stainless steel.

welding procedure schedule for the gas tungsten arc welding process for stainless steel.

The gas metal arc welding process is widely used for thicker materials since it is a faster welding process. The spray transfer mode is used for flat-position welding and this requires the use of argon for shielding with 2% or 5% oxygen or special mixtures. The oxygen helps produce better wetting action on the edges of the weld. Figure 16-11 shows the welding procedure schedule for gas metal arc welding. The short-circuiting transfer can also be used on thinner materials. In this case, CO_2 shielding or the 25% CO_2 plus 75% argon mixture is used. The argon–oxygen mixture can also be used with small-diameter electrode wires. With extra-low-carbon electrode wires and CO_2 shielding the amount of carbon pickup will increase slightly. This should be related to the service life of the weldment. If corrosion resistance is a major factor the CO_2 gas or the CO_2–argon mixture should not be used.

Stainless steel can also be welded with the submerged arc welding process. In this case, the electrode wire would be the same as shown in the selection guide table. The submerged arc flux must be selected for stainless steel welding.

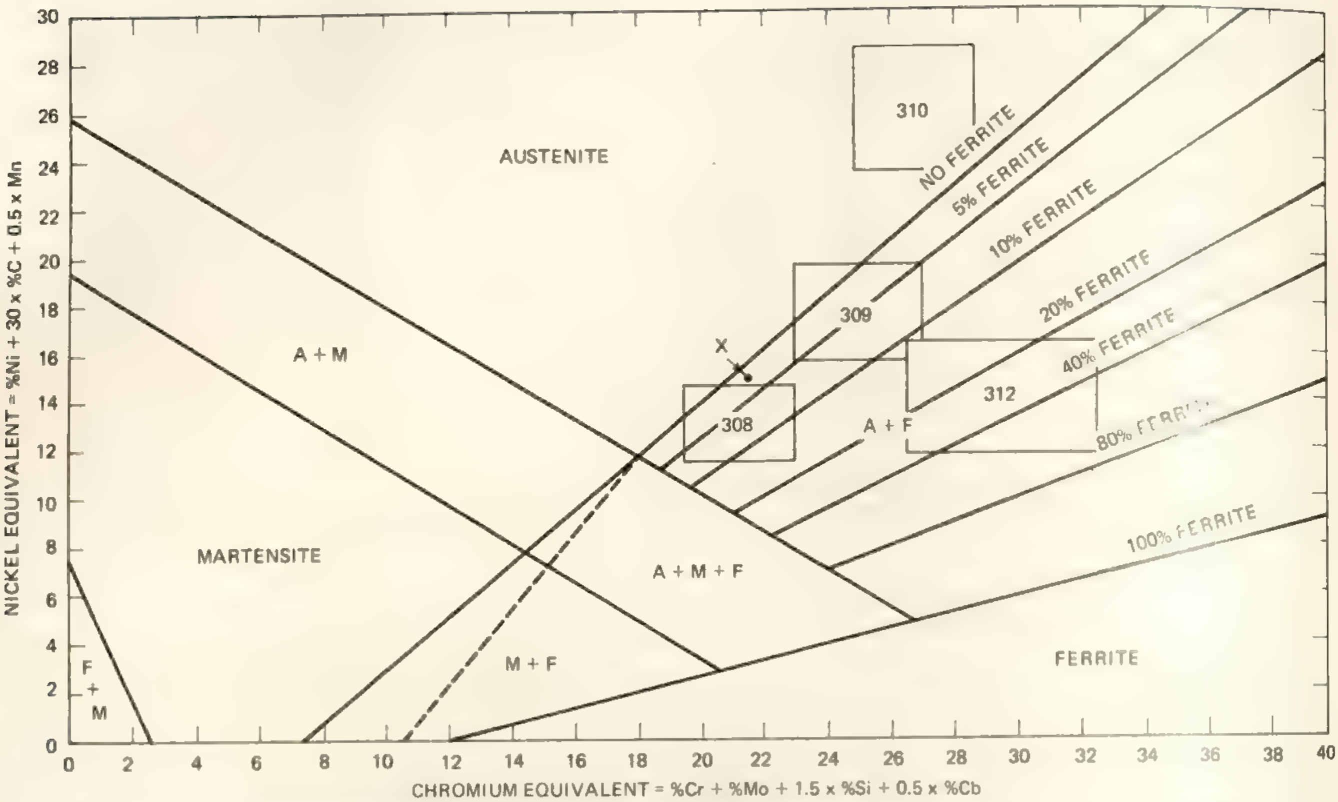
For all welding operations, the weld area should be cleaned and free from all foreign material, oil, paint, dirt, and so on. The welding arc should be as short as possible when using any of the arc processes.

Problem Areas

The most serious problem when welding stainless steels is to avoid carbide precipitation. As mentioned previously, this may occur when the material is held at a high temperature for a long period. Electrodes containing extra low carbon, indicated by the suffix L, should be used. Most electrodes are stabilized with columbium or titanium. This also helps to eliminate the carbide precipitation problem. These are definitely required when the weldment will be subjected to high temperature service.

Another factor that affects the quality of austenitic weld joints is the control of ferrite content in the microstructure. Austenitic weld deposits may develop microcracks during welding if ferrite is not controlled. The composition of the filler metal should be selected based on the deposit containing a small percentage of ferrite. The ferrite content should not become too high or else the weldment will have lower than desired impact strength. For low-temperature service the weld metal should have the ferrite in the range 4 to 10%. The ferrite content of the weld deposit depends on the composition of the base metal as well as the composition of the deposited filler metal. A special constitution diagram for stainless steel weld metal has been designed by Schaeffler and modified by DeLong.[9] This diagram (Figure 16-12) relates the nickel and chromium equivalents to lines which show the percentage of ferrite. This diagram is useful for estimating the microstructure of the weld deposit and the filler metal composition required to produce the prescribed amount of ferrite in the deposit. The diagram shows how the microstructure of the weld deposit is affected by the alloying elements in the stainless steel, based on those that act like nickel and those that act like chromium. The nickel equivalent group includes nickel and the effect of carbon and manganese. The chromium equivalent group includes chromium and the effect of molybdenum, silicon, and columbium. To estimate the microstructure of a deposit the nickel and the chromium equivalents are calculated using the following formulas:

$$\text{nickel equiv.} = \%\text{Ni} + 30\%\ \text{C} + 0.5\%\ \text{Mn}$$
$$\text{chromium equiv.} = \%\text{Cr} + \%\text{Mo} + 1.5\%\ \text{Si} + 0.5\%\ \text{Cb}$$



Example: Point X on the diagram indicates the equivalent composition of a type 318 (316 CB) weld deposit containing 0.07 C, 1.55 Mn, 0.57 Si, 18.02 Cr, 11.87 Ni, 2.16 Mo, 0.80 Cb. Each of these percentages was multiplied by the "potency factor" indicated for the element in question along the axes of the diagram, in order to determine the chromium equivalent and the nickel equivalent. When these were plotted, as point X, the constitution of the weld was indicated as austenite plus from 0 to 5% ferrite, magnetic analysis of the actual sample revealed an average ferrite content of 2%.

For austenite-plus-ferrite structures, the diagram predicts the percentage ferrite within 4% for the following stainless steels: 308, 309, 309 Cb, 310, 312, 316, 31[illegible] 316 Cb), and 347.

Dashed line is the marte[illegible] F boundary modicifation by Eberhard Le[illegible] Mechanische Eigenschaften und Gefugea[illegible]g von mit Chrom und Nickel legiertem S[illegible]issgut," VEB Deutscher Verlag fur Grundsto[illegible]ndustrie, Leipzig, 1966.

FIGURE 16-12 Constitution diagram for stainless steel weld metal. (From *Metal Progress Data Book*, ©American Society for Metals, 1977.)

The values obtained are marked on the coordinates of the diagram and a point is located. The microstructure at that point is the one predicted for a deposit of that composition. It is possible to plot the composition of the filler wire and the composition of the base metals and connect them with a line and a resulting weld would be along this line. By the use of the Schaeffler–DeLong diagram, it is possible to select a filler metal that will avoid ferrite or martensite in the stainless steel weld deposit. The diagram can also be used to predict weld deposit composition when welding dissimilar stainless steels.[10]

The stainless steels can be welded by resistance welding and by many of the other specialty welding processes. Stainless steels can also be soldered and brazed.

Removal of Weld Discoloration of Stainless Steel

It is sometimes difficult to remove heat discoloration from weld seams, especially on inside corners. It can be removed by grinding, but this may be impractical or expensive. Commercial stainless steel chemical cleaners are available and are widely used to clean stainless steel to prevent corrosion and contamination, and are used on food-processing equipment, chemical-processing equipment, metal furniture, tanks, transportation equipment, and so on. Most systems use the paste, which is painted on the surface and allowed to soak for 10 to 15 minutes, after which it is removed by using a stainless steel wire brush. It is usually available from local supply houses.

16-4 WELDING ULTRA-HIGH-STRENGTH STEELS

The term ***high-strength steel*** is often applied to all steels other than mild low-carbon steels. The steels under discussion in this section are those that have a yield strength of at least 80,000 psi (56 kg/mm²). These are sometimes called the ultra-high-strength steels or super alloys.

The groups of steels that fall into this category are:

1. Medium-carbon low-alloy hardenable steels
2. Medium-alloy hardenable or tool and die steels
3. High-alloy hardenable steels
4. High-nickel maraging steels
5. Martensitic stainless steels
6. Semiaustenitic precipitation-hardenable stainless steels

Each of these groups will be briefly described and welding information will be presented. Nominal compositions of steels in each of these groups is shown in Figure 16-13.

Medium-Carbon Low-Alloy Hardenable Steels

The best known steels in this class are the AISI 4130 and AISI 4140 steels. Also in this class are the higher-strength AISI 4340 steel and the AMS 6434 steel. These steels obtain their high strength by heat treatment to a full martensitic microstructure, which is tempered to improve ductility and toughness. Tempering temperatures greatly affect the strength levels of these steels. The carbon is in the medium range and as low as possible but sufficient to give the required strength. Impurities are kept to an absolute minimum because of high-quality melting and refining methods. These steels are available as sheets,

FIGURE 16-13 Nominal composition of ultrahigh-strength steels.

	Composition, Weight Percent						
Designation	C	Mn	Si	Cr	Ni	Mo	Other
Medium carbon low alloy hardenable steels							
AISI 4130	0.28/0.33	0.40/0.60	0.20/0.35	0.80/1.10	–	0.15/0.25	–
AISI 4140	0.38/0.43	0.75/1.0	0.20/0.35	0.80/1.10	–	0.15/0.25	–
AISI 4340	0.38/0.43	0.60/0.80	0.20/0.35	0.70/0.90	1.65/2.00	0.20/0.30	–
AMS 6434	0.31/0.38	0.60/0.80	0.20/0.35	0.65/0.90	1.65/2.00	0.30/0.40	0.17/0.23V
Medium alloy hardenable tool and die steels							
5Cr-Mo-V Aircraft Steel	0.37/0.43	0.20/0.40	0.80/1.20	4.75/5.25	–	1.20/1.40	0.4/0.6 V
H-11 Tool Steel	0.30/0.40	0.20/0.40	0.80/1.20	4.75/5.50	–	1.25/1.75	0.30/0.50 V
H-13 Tool Steel	0.30/0.40	0.20/0.40	0.80/1.20	4.75/5.50	–	1.25/1.75	0.80/1.20 V
High alloy hardenable steels							
HP 9-4-20	0.20	0.30	0.10 max	0.75	9.0	0.75	0.01-S, 0.01-P, 0.10-V, 4.50-Co
HP 9-4-30 (Cr,Mo)	0.30	0.20	0.10 max	1.00	7.5	1.00	0.01-S, 0.01-P, 0.10-V, 4.50-Co
High nickel maraging steels							
18Ni	0.03 max	0.10 max	0.10 max	–	18.0	3.25	0.01-S, 0.01-P, 8.5-Co, 0.20-Ti, 0.10-Al
18Ni	0.03 max	0.10 max	0.10 max	–	18.0	4.90	0.01-S, 0.01-P, 8.0-Co, 0.40-Ti, 0.10-Al
18Ni	0.03 max	0.10 max	0.10 max	–	17.5	4.90	0.01-S, 0.01-P, 9.0-Co, 0.65-Ti, 0.10-Al
18 Ni	0.01 max	0.10 max	0.10 max	–	17.5	3.75	0.01-S, 0.01-P, 12.5-Co, 1.80-T., 0.15-Al
Martensitic stainless steels							
AISI 420	0.15 max.	1.0 max	1.0 max	13	–	–	–
AISI 431	0.20 max	1.0 max	1.0 max	16	2.0	–	–
12MoV	0.25	0.5	0.5	12	0.5	1.0	0.3-V
17-4PH	0.07 max	1.0 max	1.0 max	16.5	4.0	–	4.0-Cu, 0.3-Cb
PH13-8Mo	0.05 max	0.1 max	0.1 max	12.5	8.0	2.5	1.1-Al
Pyromet X-15	0.03 max	0.1	0.1 max	15	–	2.9	20.0-Co
Custom 455	0.05 max	0.5 max	0.5 max	12	8.5	0.5	2.0-Cu, 0.3-Cb, 1.1-Ti
AFC 77	0.15	–	–	14.5	–	5.0	4.0-Cu, 13.5-Co, 0.5-V, 0.5-N
Semi-austenitic precipitation—hardenable stainless steels							
17-7PH	0.09 max	1.0 max	1.0 max	17.0	7.0	–	1.0-Al
PH15-7Mo	0.09 max	1.0 max	1.0 max	15.0	7.0	2.5	1.1-Al
PH14-8Mo	0.05 max	0.1 max	0.1 max	15.0	8.5	2.5	1.0-Al
AM 350	0.12 max	0.90	0.5 max	16.5	4.5	3.0	0.10-N
AM 355	0.15 max	0.95	0.5	15.5	4.5	3.0	0.09-N

bars, tubing, and light plate. The steels in this group can be mechanically cut or flame cut. However, when they are flame cut they must be preheated to 600°F (316°C). Flame-cut parts should be annealed before additional operations in order to reduce the hardness of the flame-cut edges.

Welding is usually done on these steels when they are in the annealed or normalized condition. They are then heat treated to obtain the desired strength. The gas tungsten arc, the gas metal arc, the shielded metal arc, and the gas welding process are all used for welding these steels. The composition of the filler metal is designed to produce a weld deposit that responds to a heat treatment in approximately the same manner as the base metal. In order to avoid brittleness and the possibility of cracks during welding relatively high preheat and interpass temperatures are used. Preheating is on the order of 600°F (316°C). Complex weldments are heat treated immediately after welding.

Aircraft engine mounts, aircraft tubular frames, and racing car frames are made from AISI 4130 tubular sections. These types of structures are normally not heat treated after welding.

Medium-Alloy Hardenable Steels

These steels are used largely in the aircraft industry for ultra-high-strength structural applications. They have carbon in the low to medium range and possess good fracture toughness at high strength levels. In addition, they are air hardened which reduces the distortion that is encountered with more drastic quenching methods. Some of the steels in this group are known as hot work die steels and another grade has become known as 5CR-MO-V aircraft quality steel. There are proprietory names for other steels in this class. The steels are available as forging billets, bars, sheet, strip, and plate.

There is another type of steel in this general class, which is a medium-alloy quenched and tempered steel known as high-yield or HY 130/150. This type of steel is used for submarines, aerospace applications, and pressure vessels, and is normally available as plate. This steel has good notch toughness properties at 0°F and below. These types of steels have much lower carbon than the grades mentioned previously.

When flame cutting or welding the aircraft quality steels, preheating is absolutely necessary since the steels are air hardening. A preheat of 600°F (316°C) is used before flame cutting and then annealed immediately after the flame cutting operation. This will avoid a brittle layer at the flame-cut edge which is susceptible to cracking. This type of steel should only be welded in the annealed condition. The steel should be preheated to 600°F (316°C) and this temperature must be maintained throughout the welding operation. After welding, the work must be cooled slowly. This can be done by postheating, or by furnace cooling. The weldment is then stress relieved at 1300°F (704°C) and air cooled to obtain a fully tempered microstructure suitable for additional operations. It is usually annealed, after all welding is done, prior to final heat treatment. The filler metal should be of the same composition as the base metal. The gas tungsten arc and gas metal arc processes are most widely used. However, shielded metal arc welding, plasma arc, and electron beam welding processes can be used.

The medium-alloy quenched and tempered high-yield strength steels are usually welded with the shielded metal arc, gas metal arc, or the submerged arc welding process. The filler metal must provide deposited metal of a strength level equal to the base material. In all cases, a low-hydrogen or no-hydrogen process is required. For shielded metal arc welding the low-hydrogen electrodes of the E-13018 type are recommended. Electrodes must be properly stored. In the case of the other processes, precautions should be taken to make sure that the gas is dry and that the submerged arc flux is dry. By employing the proper heat input–heat output procedure yield strength and toughness are maintained. Preheating should be at least 100°F (38°C) for thinner materials and double that for heavier materials. The heat input should be such that the adjacent base metal does not become overheated. The heat input is sufficient to maintain the proper microstructure in the heat-affected zone. There may be some softening in the intermixing zone. The properties of welded joints that are properly made will be in the same order as the base metal. Subsequent heat treating is usually not required or desired.

High-Alloy Hardenable Steels

The steels in this group develop high strength by standard hardening and tempering heat treatments. The steels possess extremely high strength in the range of 180,000 psi yield and have a high degree of toughness. This is obtained with a minimum carbon content usually in the range of 0.20%; however, these steels contain relatively high amounts of nickel and cobalt, and they are sometimes called the 9% Ni–4% Co steels. These steels also contain small amounts of other alloys. They are normally welded in the quenched and tempered condition by the gas tungsten arc welding process. No postheat treatment is required. The filler metal must match the analysis of the base metal.

High-Nickel Maraging Steels

This type of steel has a relatively high nickel content but is a low-carbon steel. It obtains its high strength from a special heat treatment called *maraging*. These steels possess an extraordinary combination of ultra-high-

strength and fracture toughness and at the same time are formable, weldable, and easy to heat treat. There are three basic types: the 18% nickel, the 20% nickel, and the 25% nickel types. These steels are available in sheet, forging billets, bars, strip, and plate. Some are available as tubing.

The extra special properties of these steels are obtained by heating the steel to 900 °F (482 °C) and allowing it to cool to room temperature. During this heat treatment all of the austenite transforms to martensite, which is of the very tough massive type. The time at the 900 °F temperature is extremely important and usually is in the range of three hours. The steels derive their strength while aging at this temperature in the martensitic condition and for this reason are known as maraging steels.

These steels are supplied in the soft or annealed condition. They can be cold worked in this condition and can be flame cut or plasma arc cut. Plasma arc cutting is preferred. These steels are usually welded by the gas tungsten arc or the gas metal arc welding process. The shielded metal arc and submerged arc process can also be used with special electrode-flux combinations. The filler metal should have the same composition as the base metal. In addition, the filler metal must be of high purity with low carbon. Preheat or postheat is not required; however, the welding must be followed by the maraging heat treatment which produces weld joints of an extremely high strength.

Martensitic Stainless Steels

These steels are of the straight chromium type, essentially the AISI 420 classification. These steels contain 12 to 14% chromium and up to 0.35% carbon. This composition combines corrosion resistance with high strength. Numerous variations of this basic composition are available, all of which are in the martensitic classification. This type of steel has been used for compressor and turbine blades of jet engines and for other applications in which moderate corrosion resistance and high strength are required. The strength level of these steels is obtained by a quenching and tempering heat treatment. They can be obtained as sheet, strip, tubing, and plate. The compositions are also used for castings. These steels can be heat treated to strengths as high as 250,000 psi (175 kg/mm^2) yield strength.

These stainless steels can be flame cut by the powder cutting system normally used for flame cutting stainless steels. They can also be cut with the oxy-arc process. Flame cutting should be done with the steel in the annealed condition. Most grades should be preheated to 600 °F (316 °C) because they are air hardenable. They should be annealed after cutting to restore softness and ductility. These materials can also be cold worked in the annealed condition.

The martensitic stainless steels can be welded in the annealed or fully hardened condition, usually without preheat. The gas tungsten arc welding process is normally used. The filler metal must be of the same analysis as the base metal. Following welding the weldment should be annealed and then heat treated to the desired strength level.

Semiaustenitic Precipitation-Hardenable Stainless Steels

The steels in this group are chrome-nickel steels that are ductile in the annealed condition but can be hardened to high strength by proper heat treatment. In the annealed condition the steels are austenitic and can be readily cold worked. By special heat treatment the austenite is transformed to martensite and later a precipitant is formed in the martensite. The outstanding extra high strength is obtained by a combination of these two hardening processes. The term *semiaustenitic type* was given these steels to distinguish them from normal stainless steels. They are also called precipitation hardening (PH) steels. The heat treatment for these steels is based on heating the annealed material to a temperature of 1700 to 1750 °F (927 to 954 °C) followed by a tempering or aging treatment in the range 850 to 1100 °F (454 to 593 °C). These steels are available as billets, sheet, tubing, and plate.

These steels are normally not flame cut. Welding is performed using the gas tungsten arc or the gas metal arc welding process. The shielded metal arc welding process is rarely used. The filler metal should have the same composition as the base metal. No preheat is required if the parts are welded in the annealed condition. Following welding it should be annealed and then heat treated to develop optimum strength levels.

It is possible to weld the PH steels in the heat-treated condition using the gas tungsten arc or gas metal arc welding process. However, there is a loss of joint strength due to heating of the heat-affected zone above the aging temperature. In view of this, it is not possible to produce a 100% efficient joint. Extra reinforcing must be utilized to develop full-strength joints. These steels are also brazed using nickel alloy filler metal.

When welding on any of these high-strength steels, weld quality must be of the highest degree. Root fusion must be complete, and there should be no undercut or any type of stress risers. The weld metal should be free of porosity and any weld cracking is absolutely unacceptable. All precautions must be taken in order to produce the highest weld quality. Arc strikes should be the basis for rejection.

QUESTIONS

16-1. What is the maximum carbon content for low-carbon steels?

16-2. Why are the free-machining steels difficult to weld?

16-3. Can the E60XX and E70XX electrodes be used to weld all carbon and mild steels?

16-4. What is the significance of the covered electrode class suffix letter?

16-5. Why can a cellulosic electrode be used to weld pipelines made of high-strength steels?

16-6. How is the electrode class suffix letter used to select electrodes for alloy steels?

16-7. How are the first two (or three) digits useful in selecting electrodes for alloy steels?

16-8. What are weathering steels? Name two popular brands.

16-9. Why is carbon-moly steel selected for high-temperature service? How is it welded?

16-10. What is the advantage of high-nickel steel for low-temperature service? How is it welded?

16-11. What are the advantages of quenched and tempered steels for construction equipment?

16-12. Why is heat input important when welding quenched and tempered steels?

16-13. What are the three types of stainless steel? Are any magnetic? Which?

16-14. Why is the welding of austenitic stainless steel different from mild steel?

16-15. Are the stainless steel covered electrodes of the low-hydrogen type? Why?

16-16. What is a duplex stainless steel?

16-17. What use is made of the Schaeffler diagram?

16-18. Can any of the ultra-high-strength steels be welded after heat treatment?

16-19. What is maraging steel? What processes are used for welding?

16-20. What is a PH steel? Can it be welded with SMAW?

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17

Welding the Nonferrous Metals

OUTLINE

17-1 ALUMINUM AND ALUMINUM ALLOYS

The unique combination of light weight and relatively high strength makes aluminum the second most popular metal that is welded. Aluminum is not difficult to join but aluminum welding is different from welding steels.

Many alloys of aluminum have been developed and it is important to know which alloy is to be welded. A system of four-digit numbers has been developed by the Aluminum Association, Inc., and adopted by ASTM to designate the wrought aluminum alloy types.[1] UNS designations are also shown; this adds A9 ahead of the AA number. This system of alloy groups (Figure 17-1) is as follows:

- *1XXX series*. These are aluminums of 99% or higher purity. They are used primarily in the electrical and chemical industires.
- *2XXX series*. Copper is the principal alloy in this group. This group provides extremely high strength when properly heat treated. These alloys do not produce as good corrosion resistance and are often clad with pure aluminum or special-alloy aluminum. These alloys are used in the aircraft industry.

Major Alloying Element	Designation
99.0% minimum aluminum and over	1xxx
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium and silicon	6xxx
Zinc	7xxx
Other element	8xxx

FIGURE 17-1 **Designation of aluminum alloy groups.**

- *3XXX series*. Manganese is the major alloying element in this group. These alloys are non-heat-treatable. Manganese is limited to about 1.5%. These alloys have moderate strength and are easily worked.
- *4XXX series*. Silicon is the major alloying element in this group. It can be added in sufficient quantities to reduce substantially the melting point and is used for brazing alloys and welding electrodes. Most of the alloys in this group are non-heat-treatable.
- *5XXX series*. Magnesium is the major alloying element of this group. These alloys are of medium strength. They possess good welding characteristics, good resistance to corrosion, but the amount of cold work should be limited.
- *6XXX series*. Alloys in this group contain silicon and magnesium which make them heat treatable. These alloys possess medium strength and good corrosion resistance.
- *7XXX series*. Zinc is the major alloying element in this group. Magnesium is also included in most of these alloys. Together they result in a heat-treatable alloy of very high strength. This series is used for aircraft frames.

The composition of the wrought aluminum alloys is shown in Figure 17-2.

Aluminum alloy casting alloys are also designated by the Aluminum Association. Figure 17-3 shows the nominal chemical composition of casting alloys. With respect to welding, it is the composition that is important rather than how the part was made. Castings as well as wrought forms are heat treated, and must be considered. Otherwise, the welding procedures can be essentially the same.

Temper Designation System

The Aluminum Association and ASTM provides a temper designation system used for wrought and cast aluminum alloys. It is based on the sequence of treatments to produce various tempers. In specifying an alloy the temper designation follows the alloy designation separated by a dash. Basic temper designations consist of letters. Subdivisions of the basic tempers, when required, are indicated by one or more digits following the letter.

The basic temper designations and subdivisions are as follows:

F As fabricated

O Annealed, recrystalized (wrought products only); applies to the softest tempers of the wrought products.

H Strain hardened (wrought products only). This applies to products which have their strength increased by strain hardening with or without supplementary treatment. The H is always followed by two or more digits. The first digit indicates the specific combination of basic operations as follows:

H-1 Strain hardened only.

H-2 Strain hardened and then partially annealed.

H-3 Strain hardened and then stabilized

The digit following the designation H-1, H-2, and H-3 indicates the final degree of strain hardening. Tempers between 0 (annealed) and 8 (full hard) are designated by Nos. 1 through 7. Numeral 2 indicates quarter hard, the numeral 4 indicates half hard, the numeral 6 indicates three-quarters hard, etc. The numeral 9 indicates extra hard temper.

The third digit, when used, indicates a variation of the two-digit H temper number.

W Solution heat treated. This is an unstable temper applied only to alloys which age harden at room temperatures after solution heat treatment.

T Thermally treated to produce stable tempers other than F, O, or H. The T is always followed by one or more digits as follows:

- T-1 Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition.
- T-2 Annealed (cast products only).
- T-3 Solution heat treated and then cold worked.
- T-4 Solution heat treated and naturally aged to a substantially stable condition.
- T-5 Cooled from an elevated temperature shaping process and then artificially aged.
- T-6 Solution heat treated and then artificially aged.
- T-7 Solution heat treated and then stabilized.
- T-8 Solution heat treated and then heat treated, cold worked, and then artificially aged.
- T-9 Solution heat treated, artificially aged, and then cold worked.

UNS Number	AA Designation	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Others Each	Others Total	Aluminum Min.
—	1050	0.25	0.40	0.05	0.05	0.05	—	—	0.05	0.03	0.03	—	99.50
A91060	1060	0.25	0.35	0.05	0.05	0.03	—	—	0.05	0.03	0.03	—	99.60
A91100	1100	1.0	Si + Fe	0.05–0.20	0.05	—	—	—	0.10	—	0.05	0.15	99.00
A91145	1145	0.55	Si + Fe	0.05	0.05	0.05	—	—	0.05	0.03	0.03	—	99.45
—	1175	0.15	Si + Fe	0.10	0.10	0.02	—	—	0.04	0.02	0.02	—	99.75
—	1200	1.0	Si + Fe	0.05	0.05	—	—	—	0.10	0.05	0.05	0.15	99.00
A91230	1230	0.7	Si + Fe	0.10	0.05	0.05	—	—	0.10	0.03	0.03	—	99.30
A91235	1235	0.65	Si + Fe	0.05	0.05	0.05	—	—	0.10	0.03	0.03	—	99.35
—	1345	0.30	0.40	0.10	0.05	0.05	—	—	0.05	0.03	0.03	—	99.45
—	1350	0.10	0.40	0.05	0.01	—	0.01	—	0.05	—	0.03	0.10	99.50
A92011	2011	0.40	0.7	5.0–6.0	—	—	—	—	0.30	—	0.05	0.15	Remainder
A92014	2014	0.50–1.2	0.7	3.9–5.0	0.40–1.2	0.20–0.8	0.10	—	0.25	0.15	0.05	0.15	Remainder
A92017	2017	0.20–0.8	0.7	3.5–4.5	0.40–1.0	0.40–0.8	0.10	—	0.25	0.15	0.05	0.15	Remainder
A92018	2018	0.9	1.0	3.5–4.5	0.20	0.45–0.9	0.10	1.7–2.3	0.25	—	0.05	0.15	Remainder
A92024	2024	0.50	0.50	3.8–4.9	0.30–0.9	1.2–1.8	0.10	—	0.25	0.15	0.05	0.15	Remainder
A92025	2025	0.50–1.2	1.0	3.9–5.0	0.40–1.2	0.05	0.10	—	0.25	0.15	0.05	0.15	Remainder
—	2036	0.50	0.50	2.2–3.0	0.10–0.40	0.30–0.6	0.10	—	0.25	0.15	0.05	0.15	Remainder
A92117	2117	0.8	0.7	2.2–3.0	0.20	0.20–0.50	0.10	—	0.25	—	0.05	0.15	Remainder
A92124	2124	0.20	0.30	3.8–4.9	0.30–0.9	1.2–1.8	0.10	—	0.25	0.15	0.05	0.15	Remainder
A92218	2218	0.9	1.0	3.5–4.5	0.20	1.2–1.8	0.10	1.7–2.3	0.25	—	0.05	0.15	Remainder
A92219	2219	0.20	0.30	5.8–6.8	0.20–0.40	0.02	—	—	0.10	0.02–0.10	0.05	0.15	Remainder
—	2319	0.20	0.30	5.8–6.8	0.20–0.40	0.02	—	—	0.10	0.10–0.20	0.05	0.15	Remainder
A92618	2618	0.10–0.25	0.9–1.3	1.9–2.7	—	1.3–1.8	—	0.9–1.2	0.10	0.04–0.10	0.05	0.15	Remainder
A93003	3003	0.6	0.7	0.05–0.20	1.0–1.5	—	—	—	0.10	—	0.05	0.15	Remainder
A93004	3004	0.30	0.7	0.25	1.0–1.5	0.8–1.3	—	—	0.25	—	0.05	0.15	Remainder
A93005	3005	0.6	0.7	0.30	1.0–1.5	0.20–0.6	0.10	—	0.25	0.10	0.05	0.15	Remainder
A93105	3105	0.6	0.7	0.30	0.30–0.8	0.20–0.8	0.20	—	0.40	0.10	0.05	0.15	Remainder
A94032	4032	11.0–13.5	1.0	0.50–1.3	—	0.8–1.3	0.10	0.50–1.3	0.25	—	0.05	0.15	Remainder
—	4043	4.5–6.0	0.8	0.30	0.05	0.05	—	—	0.10	0.20	0.05	0.15	Remainder
—	4045	9.0–11.0	0.8	0.30	0.05	0.05	—	—	0.10	0.20	0.05	0.15	Remainder
—	4047	11.0–13.0	0.8	0.30	0.15	0.10	—	—	0.20	—	0.05	0.15	Remainder
—	4145	9.3–10.7	0.8	3.3–4.7	0.15	0.15	0.15	—	0.20	—	0.05	0.15	Remainder
—	4343	6.8–8.2	0.8	0.25	0.10	—	—	—	0.20	—	0.05	0.15	Remainder
—	4643	3.6–4.6	0.8	0.10	0.05	0.10–0.30	—	—	0.10	0.15	0.05	0.15	Remainder
A95005	5005	0.30	0.7	0.20	0.20	0.50–1.1	0.10	—	0.25	—	0.05	0.15	Remainder
A95050	5050	0.40	0.7	0.20	0.10	1.1–1.8	0.10	—	0.25	—	0.05	0.15	Remainder
A95052	5052	0.25	0.40	0.10	0.10	2.2–2.8	0.15–0.35	—	0.10	—	0.05	0.15	Remainder
A95056	5056	0.30	0.40	0.10	0.05–0.20	4.5–5.6	0.05–0.20	—	0.10	—	0.05	0.15	Remainder

FIGURE 17-2 Nominal chemical composition of aluminum-wrought alloys. (Courtesy of the American Aluminum Association.)

UNS Number	AA Designation	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Titanium	Others Each	Others Total	Aluminum Min.
A95083	5083	0.40	0.40	0.10	0.40–1.0	4.0–4.9	0.05–0.25	—	0.25	0.15	0.05	0.15	Remainder
A95086	5086	0.40	0.50	0.10	0.20–0.7	3.5–4.5	0.05–0.25	—	0.25	0.15	0.05	0.15	Remainder
A95154	5154	0.45	Si + Fe	0.10	0.10	3.1–3.9	0.15–0.35	—	0.20	0.20	0.05	0.15	Remainder
—	5183	0.40	0.40	0.10	0.50–1.0	4.3–5.2	0.05–0.25	—	0.25	0.15	0.05	0.15	Remainder
A95252	5252	0.08	0.10	0.10	0.10	2.2–2.8	—	—	0.05	—	0.05	0.15	Remainder
A95254	5254	0.45	Si + Fe	0.05	0.01	3.1–3.9	0.15–0.35	—	0.20	0.05	0.05	0.15	Remainder
—	5356	0.50	Si + Fe	0.10	0.05–0.20	4.5–5.5	0.05–0.20	—	0.10	0.06–0.20	0.05	0.15	Remainder
A95454	5454	0.45	0.4	0.10	0.50–1.0	2.4–3.0	0.05–0.20	—	0.25	0.20	0.05	0.15	Remainder
A95456	5456	0.40	Si + Fe	0.10	0.50–1.0	4.7–5.5	0.05–0.20	—	0.25	0.20	0.05	0.15	Remainder
A95457	5457	0.08	0.10	0.20	0.15–0.45	0.8–1.2	—	—	0.05	—	0.03	0.10	Remainder
—	5554	0.40	Si + Fe	0.10	0.50–1.0	2.4–3.0	0.05–0.20	—	0.25	0.05–0.20	0.05	0.15	Remainder
—	5556	0.40	Si + Fe	0.10	0.50–1.0	4.7–5.5	0.05–0.20	—	0.25	0.05–0.20	0.05	0.15	Remainder
A95652	5652	0.40	Si + Fe	0.04	0.01	2.2–2.8	0.15–0.35	—	0.10	—	0.05	0.15	Remainder
—	5654	0.45	Si + Fe	0.05	0.01	3.1–3.9	0.15–0.35	—	0.20	0.05–0.15	0.05	0.15	Remainder
A95657	5657	0.08	0.10	0.10	0.03	0.6–1.0	—	—	0.05	—	0.02	0.05	Remainder
A96003	6003	0.35–1.0	0.6	0.10	0.08	0.8–1.5	0.35	—	0.20	0.10	0.05	0.15	Remainder
A96005	6005	0.6–0.9	0.35	0.10	0.10	0.40–0.6	0.10	—	0.10	0.10	0.05	0.15	Remainder
A96053	6053	—	0.35	0.10	—	1.1–1.4	0.15–0.35	—	0.10	—	0.05	0.15	Remainder
A96061	6061	0.40–0.8	0.7	0.15–0.40	0.15	0.8–1.2	0.04–0.35	—	0.25	0.15	0.05	0.15	Remainder
A96063	6063	0.20–0.6	0.35	0.10	0.10	0.45–0.9	0.10	—	0.10	0.10	0.05	0.15	Remainder
A96066	6066	0.9–1.8	0.50	0.7–1.2	0.6–1.1	0.8–1.4	0.40	—	0.25	0.20	0.05	0.15	Remainder
A96070	6070	1.0–1.7	0.50	0.15–0.40	0.40–1.0	0.50–1.2	0.10	—	0.25	0.15	0.05	0.15	Remainder
A96101	6101	0.30–0.7	0.50	0.10	0.03	0.35–0.8	0.03	—	0.10	—	0.03	0.10	Remainder
A96151	6151	0.6–1.2	1.0	0.35	0.20	0.45–0.8	0.15–0.35	—	0.25	0.15	0.05	0.15	Remainder
—	6162	0.40–0.8	0.50	0.20	0.10	0.7–1.1	0.10	—	0.25	0.10	0.05	0.15	Remainder
A96201	6201	0.50–0.3	0.50	0.10	0.03	0.6–0.9	0.03	—	0.10	—	0.03	0.10	Remainder
A96253	6253	—	0.50	0.10	—	1.0–1.5	0.15–0.35	—	1.6–2.4	—	0.05	0.15	Remainder
A96262	6262	0.40–0.8	0.7	0.15–0.40	0.15	0.8–1.2	0.4–0.14	—	0.25	0.15	0.05	0.15	Remainder
A96351	6351	0.7–1.3	0.50	0.10	0.40–0.8	0.40–0.8	—	—	0.20	0.20	0.05	0.15	Remainder
A96463	6463	0.20–0.6	0.15	0.20	0.05	0.45–0.9	—	—	—	—	0.05	0.15	Remainder
—	6951	0.20–0.50	0.8	0.15–0.40	0.10	0.40–0.8	—	—	0.20	—	0.05	0.15	Remainder
—	7001	0.35	0.40	1.6–2.6	0.20	2.6–3.4	0.18–0.35	—	6.8–8.0	0.20	0.05	0.15	Remainder
A97005	7005	0.35	0.40	0.10	0.20–0.7	1.0–1.8	0.06–0.20	—	4.0–5.0	0.01–0.06	0.05	0.15	Remainder
A97008	7008	0.10	0.10	0.05	0.05	0.7–1.4	0.12–0.25	—	4.5–5.5	0.05	0.05	0.15	Remainder
A97011	7011	0.15	0.20	0.05	0.10–0.30	1.0–1.6	0.05–0.20	—	4.0–5.5	0.05	0.05	0.15	Remainder
A97072	7072	0.7	Si + Fe	0.10	0.10	0.10	—	—	0.8–1.3	—	0.05	0.15	Remainder
A97075	7075	0.40	0.50	1.2–2.0	0.30	2.1–2.9	0.18–0.35	—	5.1–6.1	0.20	0.05	0.15	Remainder
—	7079	0.30	0.40	0.40–0.8	0.10–0.30	2.9–3.7	0.10–0.25	—	3.8–4.8	0.10	0.05	0.15	Remainder
A97178	7178	0.40	0.50	1.6–2.4	0.30	2.4–3.1	0.18–0.35	—	6.3–7.3	[illegible]	[illegible]	0.15	Remainder

Notes: 1. Composition is percent maximum unless shown as a range, or a minimum.
2. There are sometimes other minor elements present. See the reference for exact data.

FIGURE 17-2 (*cont.*)

AA Number	Former Designation	Product	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Nickel	Zinc	Tin	Titanium	Others Each	Others Total
208.0	108	S	2.5–3.5	1.2	3.5–4.5	0.50	0.10	—	0.35	1.0	—	0.25	—	0.50
213.0	C113	P	1.0–3.0	1.2	6.0–8.0	0.6	0.10	—	0.35	2.5	—	0.25	—	0.50
222.0	122	S&P	2.0	1.5	9.2–10.7	0.50	0.15–0.35	—	0.50	0.8	—	0.25	—	0.35
242.0	142	S&P	0.7	1.0	3.5–4.5	0.35	1.2–1.8	0.25	1.7–2.3	0.35	—	0.25	0.05	0.15
295.0	195	S	0.7–1.5	1.0	4.0–5.0	0.35	0.03	—	—	0.35	—	0.25	0.05	0.15
B295.0	B195	P	2.0–3.0	1.2	4.0–5.0	0.35	0.05	—	0.35	0.50	—	0.25	—	0.35
308.0	A108	P	5.0–6.0	1.0	4.0–5.0	0.50	0.10	—	—	1.0	—	0.25	—	0.50
319.0	319, Allcast	S&P	5.5–6.5	1.0	3.0–4.0	0.50	0.10	—	0.35	1.0	—	0.25	—	0.50
328.0	Red X-8	S	7.5–8.5	1.0	1.0–2.0	0.20–0.6	0.20–0.6	0.35	0.25	1.5	—	0.25	—	0.50
A332.0	A132	P	11.0–13.0	1.2	0.50–1.5	0.35	0.7–1.3	—	2.0–3.0	0.35	—	0.25	0.05	—
F332.0	F132	P	8.5–10.5	1.2	2.0–4.0	0.50	0.50–1.5	—	0.50	1.0	—	0.25	—	0.50
333.0	333	P	8.0–10.0	1.0	3.0–4.0	0.50	0.05–0.50	—	0.50	1.0	—	0.25	—	0.50
355.0	355	S&P	4.5–5.5	0.6	1.0–1.5	0.50	0.40–0.6	0.25	—	0.35	—	0.25	0.05	0.15
C355.0	C355	S&P	4.5–5.5	0.20	1.0–1.5	0.10	0.40–0.6	—	—	0.10	—	0.20	0.05	0.15
356.0	356	S&P	6.5–7.5	0.6	0.25	0.35	0.20–0.40	—	—	0.35	—	0.25	0.05	0.15
A356.0	A356	S&P	6.5–7.5	0.20	0.20	0.10	0.20–0.40	—	—	0.10	—	0.20	0.05	0.15
357.0	357	S&P	6.5–7.5	0.15	0.05	0.03	0.45–0.6	—	—	0.05	—	0.20	0.05	0.15
360.0	360	D	9.0–10.0	2.0	0.6	0.35	0.40–0.6	—	0.50	0.50	0.15	—	—	0.25
A360.0	A360	D	9.0–10.0	1.3	0.6	0.35	0.40–0.6	—	0.50	0.50	0.15	—	—	0.25
·380.0	380	D	7.5–9.5	2.0	3.0–4.0	0.50	0.10	—	0.50	3.0	0.35	—	—	0.50
A380.0	A380	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10	—	0.50	3.0	0.35	—	—	0.50
A384.0	384	D	10.5–12.0	1.3	3.0–4.5	0.50	0.10	—	0.50	1.0	0.35	—	—	0.50
413.0	13	D	11.0–13.0	2.0	1.0	0.35	0.10	—	0.50	0.50	0.15	—	—	0.25
A413.0	A13	D	11.0–13.0	1.3	1.0	0.35	0.10	—	0.50	0.50	0.15	—	—	0.25
B443.0	43 (0.15 max. cu)	S&P	4.5–6.0	0.8	0.15	0.35	0.05	—	—	0.35	—	0.25	0.05	0.15
C443.0	A43	D	4.5–6.0	2.0	0.6	0.35	0.10	—	0.50	0.50	0.15	—	—	0.25
514.0	214	S	0.35	0.50	0.15	0.35	3.5–4.5	—	—	0.15	—	0.25	0.05	0.15
A514.0	A214	P	0.30	0.40	0.10	0.30	3.5–4.5	—	—	1.4–2.2	—	0.20	0.05	0.15
B514.0	B214	S	1.4–2.2	0.6	0.35	0.8	3.5–4.5	0.25	—	0.35	—	0.25	0.05	0.15
518.0	218	D	0.35	1.8	0.25	0.35	7.5–8.5	—	0.15	0.15	0.15	—	—	0.25
520.0	220	S	0.25	0.30	0.25	0.15	9.5–10.6	—	—	0.15	—	0.25	0.05	0.15
535.0	Almost 35	S	0.15	0.15	0.05	0.10–0.25	6.2–7.5	—	—	—	—	0.10–0.25	0.05	0.15
705.0	603, Ternalloy 5	S&P	0.20	0.8	0.20	0.40–0.6	1.4–1.8	0.20–0.40	—	2.7–3.3	—	0.25	0.05	0.15
707.0	607, Ternalloy 7	S&P	0.20	0.8	0.20	0.40–0.6	1.8–2.4	0.20–0.40	—	4.0–4.5	—	0.25	0.05	0.15
A712.0	A612	S	0.15	0.50	0.35–0.65	0.05	0.6–0.8	—	—	6.0–7.0	—	0.25	0.05	0.15
D712.0	D612, 40E	S	0.30	0.50	0.25	0.10	0.50–0.65	0.40–0.6	—	5.0–6.5	—	0.15–0.25	0.05	0.20
713.0	613, Tenzaloy	S&P	0.25	1.1	0.40–1.0	0.6	0.20–0.50	0.35	0.15	7.0–8.0	—	0.25	0.10	0.25
771.0	Precedent 71A	S	0.15	0.15	0.10	0.10	0.8–1.0	0.06–0.20	—	6.5–7.5	—	0.10–0.20	0.05	0.15
850.0	750	S&P	0.7	0.7	0.7–1.3	0.10	0.10	—	0.7–1.3	—	5.5–7.0	0.20	—	0.30
A850.0	A750	S&P	2.0–3.0	0.7	0.7–1.3	0.10	0.10	—	0.30–0.7	—	5.5–7.0	0.20	—	0.30
B850.0	B750	S&P	0.40	0.7	1.7–2.3	0.10	0.6–0.9	—	0.9–1.5	—	5.5–7.0	0.20	—	0.30

Notes: 1. Composition is percent maximum unless shown as a range. Aluminum is the remainder.
2. There may be minor elements present. See the reference for exact data.
3. Product: S, Sand cast; P, permanent mold cast; D, die cast.

FIGURE 17-3 Nominal chemical composition of aluminum-casting alloys. (Courtesy of the American Aluminum Association.)

T-10 Cooled from an elevated temperature shaping process, artificially aged, and then cold worked.

An additional digit may be used which indicates the variation and treatment that significantly alter the characteristics of the product. For example, TX indicates stress relieving by some process such as stretching, compressing or thermal treatment.

The temper designations are important from a welding point of view since welding which is normally a thermal process can change the characteristics of the metal in the heat-affected zone. Care must be taken when welding on the H, W, or T designations. Metallurgical advice should be obtained to determine treatment required to obtain original properties.

The different temper designations are used for different products such as sheet, plate, pipe, shapes, rod, bar, etc. In addition, the different alloys are available in certain types of mill products. In other words, all products are not available in all compositions nor in all of the different tempers.

The heat-treatable alloys which contain copper or zinc are less resistant to corrosion than the non-heat-treatable alloys. To increase the corrosion resistance of these alloys in sheet and plate they are somteimes clad with high-purity aluminum, usually 2½–4% of the total thickness on each side. These are known as *alclad* products.

Welding Aluminum Alloys

Aluminum possesses a number of properties that make welding different than welding steels. These are:

1. Aluminum oxide surface coating
2. High thermal conductivity
3. High thermal expansion coefficient
4. Low melting temperature
5. The absence of color change as temperature approaches the melting point

Aluminum is an active metal and it reacts with oxygen in the air to produce a thin hard film of aluminum oxide on the surface. The melting point of aluminum oxide is approximately 3600 °F (1926 °C), which is almost three times the melting point of pure aluminum, 1220 °F (660 °C). This aluminum oxide film, particularly as it becomes thicker, will absorb moisture from the air. Moisture is a source of hydrogen which is the cause of porosity in aluminum welds. Hydrogen may also come from oil, paint, and dirt in the weld area. It also comes from the oxide and foreign materials on the electrode or filler wire, as well as from the base metal. Hydrogen will enter the weld pool and is soluble in molten aluminum. As the aluminum solidifies it will retain much less hydrogen and the hydrogen is rejected during solidification. With a rapid cooling rate, free hydrogen is trapped in the weld and will cause porosity.

The aluminum oxide film must be removed prior to welding. If it is not all removed, small particles of unmelted oxide will be entrapped in the weld and will cause a reduction in ductility, lack of fusion, and may cause weld cracking.

The aluminum oxide can be removed by mechanical or chemical means or electrical means. Mechanical removal involves scraping with a sharp tool, sandpaper, wire brush (stainless steel), filing, or any other mechanical method. Chemical removal can be done in two ways. One is by use of cleaning solutions, either the etching types or the nonetching types. The nonetching types should be used only when starting with relatively clean parts. They are used in conjunction with other solvent cleaners. For better cleaning the etching type solutions are recommended but must be used with care. When dipping is employed hot and cold rinsing is recommended. The etching type solutions are alkaline solutions. The time in the solution must be controlled so that too much etching does not occur.

Chemical cleaning includes the use of welding fluxes. Fluxes are used for gas welding, brazing, and soldering. The coating on covered aluminum electrodes also contains fluxes for cleaning the base metal. Whenever etch cleaning or flux cleaning is used the flux and alkaline etching materials must be completely removed from the weld area to avoid future corrosion.

The electrical oxide removal system uses cathodic bombardment. Cathodic bombardment occurs during the half cycle of alternating current gas tungsten arc welding when the electrode is positive (reverse polarity). This is an electrical phenomenon that actually blasts away the oxide coating to produce a clean surface. This is one of the reasons why ac gas tungsten arc welding is so popular for welding aluminum.

The oxide film will immediately start to reform. The time of buildup is not extremely fast, but welds should be made after aluminum is cleaned within at least 8 hours for good quality welding.

Aluminum conducts heat from three to five times as fast as steel depending on the specific alloy. This means that more heat must be put into the aluminum even though the melting temperature of aluminum is less than half that of steel. Because of the high thermal conductivity, preheat is often used for welding thicker sections. If the temperature is too high or the period of time is too long it can be detrimental to weld joint strength in both heat-treated and work-hardened alloys. The preheat for aluminum should not exceed 400 °F (204 °C), and the parts should not be held at that temperature longer than necessary. Because of the high heat conductivity, procedures should utilize higher-speed welding processes using high

heat input. Both the gas tungsten arc and the gas metal arc processes supply this requirement.

The high heat conductivity of aluminum can also be helpful since if heat is conducted away from the weld extremely fast the weld will solidify very quickly. This with surface tension helps hold the weld metal in position and makes all-position welding practical.

The thermal expansion of aluminum is twice that of steel. In addition, aluminum welds decrease about 6% in volume when solidifying from the molten state. This change in dimension or attempt to change in dimension may cause distortion and cracking.

Aluminum does not exhibit color as it approaches its melting temperature. Aluminum will show color above the melting point, at which time it will glow a dull red. When soldering or brazing aluminum with a torch, flux is used and the flux will melt as the temperature of the base metal approaches the temperature required. The flux first dries out and then melts as the base metal reaches the correct working temperature. When torch welding with oxyacetylene or oxyhydrogen the surface of the base metal will melt first and assume a characteristic wet and shiny appearance. (This aids in knowing when welding temperatures are reached.) When welding with gas tungsten arc, or gas metal arc, color is not too important because the weld is quickly completed before the adjoining area would melt.

When the factors above are taken into consideration it will allow making welded joints in aluminum with little or no more trouble than when welding steels.

With either gas metal arc or gas tungsten arc welding the selection of filler metal is the same. The base metal composition or alloy must be known. Figure 17-4 provides the nominal composition of the different aluminum filler metals. Refer to AWS specifications A5.3 and A5.10 for details. These provide for bare, solid, straightened electrode wires, coiled wires and covered electrodes. It may not be necessary to make the comparison or selection of the filler metal to weld the different aluminum alloys since this has been fairly well standardized. Figure 17-5 is a guide to the choice of filler metals for aluminum welding established by the American Welding Society and is recommended.

Gas Tungsten Arc Welding

The gas tungsten arc welding process is used for welding the thinner sections of aluminum and aluminum alloys. Alternating current is recommended for general-purpose work since it provides the half-cycle of cleaning action. Figure 17-6 provides welding procedure schedules for using the process on different thicknesses. Ac welding, usually with high frequency, is widely used with manual and automatic applications. Procedures should be followed closely and special attention should be given to the type of tungsten electrode, size of welding nozzle, gas type, and gas flow rates. When manual welding the arc length should be kept short and equal to the diameter of the electrode. The tungsten electrode should not protrude too far beyond the end of the nozzle. The tungsten should be kept clean and if it does accidentally touch the molten metal it must be redressed.

Welding power sources designed for the gas tungsten arc welding process should be used since they provide for programming, pre- and postflow of shielding gas, and pulsing.

For automatic or machine welding direct current electrode negative (straight polarity) can be used. Cleaning must be extremely efficient since there is no cathodic bombardment to assist. When dc electrode negative is used, extremely deep penetration and high speeds can be obtained. Cleanliness is an absolute necessity. Figure 17-7 provides welding procedure schedules for dc electrode negative welding.

The gases are either argon or helium or a mixture of the two. Argon is the most popular and is used at a lower flow rate. Helium will increase penetration but a higher flow rate is required.

FIGURE 17-4 Composition of aluminum filler metals.

	Nominal Composition %								
Type	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
1100	1.0 Si + Fe		0.05-0.20	0.05	–	–	0.10	–	99.0 Min.
4043	4.5-6.0	0.80	0.30	0.05	0.05	–	0.10	0.20	Remainder
5154	0.45 Si + Fe		0.10	0.10	3.1-3.9	0.15-0.35	0.20	0.20	Remainder
5254	0.45 Si + Fe		0.05	0.01	3.1-3.9	0.15-0.35	0.20	0.05	Remainder
5652	0.40 Si + Fe		0.04	0.01	2.2-2.8	0.15-0.35	0.10	–	Remainder
5554	0.40 Si + Fe		0.10	0.50-1.0	2.4-3.0	0.05-0.20	0.25	0.05-0.20	Remainder
5356	0.50 Si + Fe		0.10	0.05-0.20	4.5-5.5	0.05-0.20	0.10	0.06-0.20	Remainder
5183	0.40	0.40	0.10	0.50-1.0	4.3-5.2	0.05-0.25	0.25	0.15	Remainder
5556	0.40 Si + Fe		0.10	0.50-1.0	4.7-5.5	0.04-0.35	0.25	0.05-0.20	Remainder
6061	0.40-0.80	0.70	0.15-0.40	0.15	0.80-1.2	0.04-0.35	0.25	0.15	Remainder

Per AWS specification A5.10 "aluminum and aluminum alloy welding rods and bare electrodes".

Base Metal	319, 333 354, 355 C355	13,43,344 356, A356 A357, 359	214, A214 B214, F214	7039,7005k A612, C612 D612	6070	6061, 6063 6101, 6151 6201, 6951	5456	5454
1060, EC 1100, 3003	4145[e,i]	4043[i,f]	4043[e,i]	4043[i]	4043[i]	4043[i]	5356[c]	4043[e]
Alclad 3003	4145[e,i]	4043[i,f]	4043[e,i]	4043[i]	4043[i]	4043[i]	5356[c]	4043[e]
2014, 2024	4145[g]	4145	—	—	4145	4145	—	—
2219	4145[g,e,i]	4145[e,i]	4043[i]	4043[i]	4043[f,i]	4043[f,i]	4043	4043[i]
3004 Alclad 3004	4043[i]	4043[i]	5654[b]	5356[e]	4043[e]	4043[b]	5356[e]	5654[b]
5005, 5050	4043[i]	4043[i]	5654[b]	5356[e]	4043[e]	4043[b]	5356[e]	5654[b]
5052,5652[a]	4043[i]	4043[b,i]	5654[b]	5356[e,h]	5356[b,c]	5356[b,e]	5356[b]	5654[b]
5083	—	5356[c,e,i]	5356[e]	5183[e,h]	5356[e]	5356[e]	5183[e]	5356[e]
5086	—	5356[c,e,i]	5356[e]	5356[e,h]	5356[e]	5356[e]	5356[e]	5356[b]
5154, 5254[a]	—	4043[b,i]	5654[b]	5356[b,h]	5356[b,c,]	5456[b,c]	5654[b]	5654[a,b]
5454	4043[i]	4043[b,i]	5654[b]	5356[b,h]	5356[b,c]	5356[b,c]	5356[b]	5654[c,e]
5456	—	5356[c,e,i]	5356[e]	5556[e,h]	5356[e]	5356[e]	5556[i]	
6961, 6063, 6101, 6201, 6151, 6951	4145[e,i]	4043[b,i]	5356[b,c]	5356[b,c,h,i]	4043[b,i]	4043[b,i]		
6070	4145[e,i]	4043[e,i]	5356[c,e]	5356[c,e,h,i]	4043[e,i]			
7039,7005[k] A612, C612 D612	4043[i]	4043[b,h,i]	5356[b,h]	5039[e]				
214, A214 B214, F214	—	4043[b,i]	5654[b,d]					
13, 43, 344 356, A356 A357, 359	4145[e,i]	4043[d,i]						
319, 333 354. 355. C355	4145[d,e,i]							

Notes: 1. Service conditions such as immersion in fresh or salt water, exposure to specific chemicals, or a sustained high temperature (over 150°F) may limit the choice of filler metals.

FIGURE 17-5 Guide to the choice of filler metal for welding aluminum.

When filler wire is used, either manually or automatically, it must be clean. If the oxide is not removed from the filler wire, it may include moisture that will tend to produce posority in the weld deposit.

Gas Metal Arc Welding

The gas metal arc welding process is applicable to heavier thicknesses of aluminum. It is much faster than the gas tungsten arc process.

Several factors should be mentioned with respect to GMAW welding aluminum. The electrode wire must be clean. Precautions should be taken when storing electrodes, so that when they are used they will produce quality welds. If porosity occurs, it is possible that it came from moisture absorbed in the oxide coating of the electrode wire.

Pure argon is normally used for gas metal arc welding of aluminum. On occasion, leaks in the gas system, in the gun or cable assembly, will allow air to be drawn into the argon which will cause porosity. Gas purge control and post-gas flow should be used. The angle of the gun or torch is critical. A 30° leading travel angle is recommended. The electrode wire tip should be oversize for aluminum. Figure 17-8 provides welding procedure schedules for gas metal arc welding of aluminum.

The wire feeding equipment for aluminum welding must be in good adjustment for efficient wire feeding. Nylon liners should be used in cable assemblies. Proper drive rolls should be selected for the aluminum wire and for the size of the electrode wire. It is difficult to push extremely small diameter aluminum wires through long gun cable assemblies. The spool gun or the newly developed guns which contain a linear feed motor are used for the small-diameter electrode wires. Water-cooled guns are required except for low-current welding.

Both the constant-current power source with matching voltage-sensing wire feeder and the constant-voltage power source with constant-speed wire feeder are used for welding aluminum. The CV system is preferred when welding on thin material and using small diameter electrode wire. It provides better arc starting and regulation. The CC system is preferred when welding thick material using larger electrode wires. The constant-current power

5154 5254[a]	5086	5083	5052 5652[a]	5005 5050	3004 Alc. 3004	2219	2014 2024	1100 3003 Alc. 3003	1060 EC	Base Metal
4043[e,i]	5356[c]	5356[c]	4043[i]	1100[c]	4043	4145	4145	1100[c]	1260[c,i]	1060, EC
4043[e,i]	5356[c]	5356[c]	4043[e,i]	4043[c]	4043[e]	4145	4145	1100[c]		1100, 3003 Alclad 3003
—	—	—	—	—	—	4145[g]	4145[g]			2014, 2024
4031[i]	4043	4043	4043[i]	4043	4043	2319[e,f,i]				2219
5654[b]	5356[c]	5356[e]	4043[e,i]	4043[e,i]	4043[e]					3004 Alclad 3004
5654[b]	5356[e]	5356[e]	4043[e,i]	4043[d,e]						5005, 5050
5654[b]	5356[e]	5356[e]	5654[a,b,c]							5052, 5652[a]
5356[c]	5356[e]	5183[e]								5083
5356[b]	5356[e]									5086

2. Recommendations in this table apply to gas-shielded arc welding processes. For gas welding, only R1100, R1260, and R4043 filler metals are ordinarily used.
3. Filler alloys designated with ER prefix are listed in AWS specification A5.10.
   [a]Base metal alloys 5652 and 5254 are used for hydrogen peroxide service. ER5654 filler metal is used for welding both alloys for low-temperature service (150°F and below).
   [b]ER5183, ER5356, ER5554, ER5556, and ER5654 may be used. In some cases they provide: (1) improved color match after anodizing treatment, (2) highest weld ductility, and (3) higher weld strength. ER5554 is suitable for elevated temperature service.
   [c]ER4043 may be used for some applications.
   [d]Filler metal with the same analysis as the base metal is sometimes used.
   [e]ER5183, ER5356, or ER5556 may be used.
   [f]ER4145 may be used for some applications.
   [g]ER2319 may be used for some applications.
   [h]ER5039 may be used for some applications.
   [i]ER4047 may be used for some applications.
   [j]ER1100 may be used for some applications.
   [k]7005 extrusions only.
4. Where no filler metal is listed, the parent alloy combination is not recommended for welding.

FIGURE 17-5 *(cont.)*

source with a moderate droop of 15 to 20 V per 100 A and with a constant-speed wire feeder provides the most stable power input and provides the highest weld quality.

The recent availability of lithium aluminum alloys has excited the aerospace industry. These alloys are approximately 10% stronger than existing alloys. This allows the use of thinner sections for weight reduction or higher-strength parts of the same weight. The problem; lithium is very active and the lithium aluminum alloys are difficult to weld. The variable-polarity power source described in the power source section with the keyhole plasma arc process is being used to weld this material in thicknesses up to ½ in. The quality of the welds exceed the quality of multipass gas tungsten arc welds. The VPPA welding process is able to make welds in one pass; however, to provide reinforcing a second pass is made. This process is used to make the longitudinal welds on the external fuel tank of the space shuttle.

Other Welding Processes

The shielded metal arc welding process can be used for welding aluminum. The covering on the electrodes is hydroscopic and must be protected from the atmosphere. Welds made with covered electrodes must be cleaned since the residue that remains on the weld will cause corrosion. Arc stability is rather poor and there are a limited number of electrode types. This process is not popular. The carbon arc welding process is of little use today.

Gas welding has been done using both oxyacetylene and oxyhydrogen flames. In either case, neutral flame is required. Flux is used as well as a filler rod. The process also is not too popular because of low heat input and the need to remove flux.

Electroslag welding is used for joining pure aluminum. So far it has not been successful for welding the aluminum alloys. Submerged arc welding has been used in some countries where inert gas is not available. It is not used in North America.

All of the resistance welding processes are used for welding aluminum. In the case of spot and seam welding, extreme cleanliness of surface is required. Different types of power are used but the process is extremely efficient and is widely used in the aircraft industry.

Most of the solid-state welding processes, including

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Tungsten Electrode Diameter in.	mm	Filler Rod Diameter in.	mm	Nozzle Size Inside Dia. in.	Shielding Gas Flow cfh	Welding Current Amps AC	No. of Passes	Travel Speed (per pass) ipm
3/64	0.046	1.2	Sq. Groove & Fillet	1/16	1.6	1/16	1.6	1/4-3/8	20	40-60	1	14-18
1/16	0.063	1.6	Sq. Groove & Fillet	3/32	2.4	3/32	2.4	5/16-3/8	20	70-90	1	8-12
3/32	0.094	2.4	Sq. Groove & Fillet	3/32	2.4	3/32	2.4	5/16-3/8	20	95-115	1	10-12
1/8	0.125	3.2	Sq. Groove & Fillet	1/8	3.2	1/8	3.2	3/8	20	120-140	1	9-12
3/16	0.187	4.7	Fillet	5/32	3.9	5/32	3.9	7/16-1/2	25	160-200	1	9-12
3/16	0.187	4.7	Vee Groove	5/32	3.9	5/32	3.9	7/16-1/2	25	160-180	2	10-12
1/4	0.250	6.4	Fillet	3/16	4.8	3/16	4.8	7/16-1/2	30	230-250	1	8-11
1/4	0.250	6.4	Vee Groove	3/16	4.8	3/16	4.8	7/16-1/2	30	200-220	2	8-11
3/8	0.375	9.5	Vee Groove	3/16	4.8	3/16	4.8	1/2	35	250-310	2-3	9-11
1/2	0.500	12.7	Vee or U Groove	1/4	6.4	1/4	6.4	5/8	35	400-470	3-4	6

1 - Increase amperage when backup is used.
2 - Data is for all welding positions. Use low side of range for out of position.
3 - For tungsten electrodes—1st choice—pure tungsten EWP; 2nd choice—zirconated EWZr.
4 - Normally Argon is used for shielding, however, mixtures of 10% or more helium with Argon are sometimes used for increased penetration in aluminum 1/4" thick and over. The gas flow should be increased when helium is added. A mixture of 75% He + 25% Argon is popular. When 100% helium is used, gas flow rates are about twice those used for Argon.

FIGURE 17-6 Welding procedure schedules for AC-GTAW of aluminum.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Tungsten Electrode Diameter in.	mm	Filler Rod Diameter in.	mm	Nozzle Size Inside Dia. in.	Shielding Gas Flow cfh	Welding Current Amps DCEN	No. of Passes	Travel Speed (per pass) ipm
20	0.032	0.8	Sq. groove & fillet	3/32	2.4	None		3/8	30	65-70	1	52
18	0.046	1.2	Sq. groove & fillet	3/64	1.2	3/64	1.2	3/8	30	35-95	1	45
16	0.063	1.6	Sq. groove & fillet	3/64	1.2	3/64	1.2	3/8	30	45-120	1	36
13	0.094	2.4	Sq. groove & fillet	1/16	1.6	1/16	1.6	3/8	30	90-185	1	32
11	1/8	3.2	Sq. groove & fillet	1/8	3.2	1/8	3.2	3/8	30	120-220	1	20
11	1/8	3.2	Sq. groove & fillet	1/8	3.2	None		3/8	30	180-200	1	24
—	1/4	6.4	Sq. groove & fillet	1/8	3.2	1/8	3.2	1/2	40	230-340	1	22
—	1/4	6.4	Sq. groove & fillet	1/8	3.2	None		1/2	40	220-240	1	22
—	1/2	12.7	Vee groove	3/16	4.8	1/8	3.2	1/2	40	300-450	1	20
—	1/2	12.7	Sq. groove	5/32	3.9	None		1/2	40	260-300	2	20
—	3/4	19.1	Vee groove	3/16	4.8	1/8	3.2	1/2	40	300-450	2	6
—	3/4	19.1	Sq. groove	3/16	4.8	None		1/2	40	450-470	2	6
—	1	25.4	Vee groove	3/16	4.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5

Normally for automatic travel
Use Helium or 75% helium 25% argon

FIGURE 17-7 Welding procedure schedules for DC-GTAW of aluminum.

Material Thickness (or Fillet Size) gs	in.	mm	Type of Weld Fillet or Groove	Electrode Diameter in.	mm	WELDING POWER Current Amps DC	Arc Volt EP	Wire Feed Speed ipm	Shielding Gas Flow cfh	No. of Passes	Travel Speed (per pass) ipm
–	0.050	–	Sq. groove & fillet	0.030	0.8	50	12-14	268-308	30	1	17-25
–	0.062	1.6	Sq. groove & fillet	0.030	0.8	55-60	12-14	295-320	30	1	17-25
–	0.062	1.6	Sq. groove & fillet	3/64	1.2	110-125	19-21	175-185	30	1	20-27
–	0.093	2.4	Sq. groove & fillet	0.030	0.8	90-100	14-18	330-370	30	1	24-36
–	0.125	3.2	Fillet	0.030	0.8	110-125	19-22	410-460	30	1	20-24
11	0.125	3.2	Sq. groove	3/64	1.2	110-125	20-24	175-190	40	1	20-24
3/16	0.187	4.7	Sq. groove & fillet	3/64	1.2	160-195	20-24	215-225	40	1	20-25
1/4	0.250	6.4	Fillet	3/64	1.2	160-195	20-24	215-225	40	1	20-25
1/4	0.250	6.4	Vee groove	1/16	1.6	175-225	22-26	150-195	40	3	20-25
3/8	0.375	9.5	Vee groove & fillet	1/16	1.6	200-300	22-26	170-275	40	2-5	25-30
1/2	0.500	12.7	Vee groove & fillet	1/16	1.6	220-230	22-27	195-205	40	3-8	12-18
1/2	0.500	12.7	Double vee groove	3/32	2.4	320-340	22-29	140-150	45	2-5	15-17
3/4	0.750	19.0	Double vee groove	1/16	1.6	255-275	22-27	230-250	50	4-10	8-18
3/4	0.750	19.0	Double vee groove	3/32	2.4	355-375	22-29	155-160	50	4-10	14-16
1	1.000	25.4	Double vee groove	1/16	1.6	255-290	22-27	230-265	50	4-14	6-18
1	1.000	25.4	Double vee groove	3/32	2.4	405-425	22-27	175-180	50	4-8	8-12

1 - For groove and fillet welds—material thickness also indicated fillet weld size. Use vee groove for 3/16" and thicker.

2 Use argon for thin and medium material; sue 50% argon and 50% helium for thick material. Increase gas flow rate 10% for overhead position.

3 - Increase amperage 10-20% when backup is used.

4 - Decrease amperage 10-20% when welding out of position.

FIGURE 17-8 Welding procedure schedules for GMAW of aluminum.

friction welding, ultrasonic welding, and cold welding, are used for aluminums. In addition, the stud welding process is used for aluminum. Aluminum can also be joined by soldering and brazing. Brazing can be accomplished by most brazing methods. A high-silicon alloy filler material is used.

Electron beam welding process is also used for aluminum welding, as are the plasma process and laser welding. These processes have not, however, been used to a very great degree.

All the major aluminum companies provide welding manuals and data for the welding of aluminum.[2-4] If more detail is required, these books are recommended.

17-2 COPPER AND COPPER-BASE ALLOYS

Copper and copper-base alloys have specific properties which make them widely used. Their high electrical conductivity makes them widely used in the electrical industries and corrosion resistance of certain alloys makes them very useful in the process industries. Copper alloys are also widely used for friction or bearing applications.

There are over 300 different alloys commercially available. All of these different alloys have been used for many years. The Copper Development Association, Inc., has established an alloy designation system that is widely accepted in North America. It is not a specification system but rather a method of identifying and grouping different coppers and copper alloys. This system has been updated so that it now fits the unified numbering system (UNS). It provides one unified numbering system which includes all of the commercially available metals and alloys. The UNS designation consists of the prefix letter C followed by a space, three digits, another space, and finally, two zeros. The compositions of each UNS number or copper alloy number and its common name is published by the association.[5]

Figure 17-9 shows the grouping of these copper alloys by common names which normally include the constituent alloys. There may be alloys within a grouping that may have a composition sufficiently different to create welding problems. These are the exception and the data presented will provide starting point guidelines. There are two categories, wrought materials and cast materials. The welding information is the same whether the material is cast or rolled.

Copper shares some of the characteristics of aluminum, but it is weldable. Attention should be given to its properties that make the welding of copper and copper alloys different from the welding of carbon steels. Copper alloys possess properties that require special attention when welding:

1. High thermal conductivity
2. High thermal expansion coefficient
3. Relatively low melting point
4. *Hot short* (i.e., brittle at elevated temperatures)
5. Very fluid molten metal
6. High electrical conductivity
7. Much of its strength due to cold working

Copper Number	Wrought Alloys—Groups
C11X00	Oxygen free–high conductivity copper (99.95+ %)
C11X00 C12X00 C13X00	Tough pitch copper (99.88+ %)
C19X00	High-copper alloys (96+ % copper)
C2XX00	Copper–zinc alloys (brasses)
C3XX00	Copper–zinc–lead alloys (leaded brasses)
C4XX00	Copper–zinc–tin alloys (tin brasses)
C50X00 C51X00 C52X00	Copper–tin alloys (phosphor bronzes)
C53X00 C54X00	Copper–tin–lead alloys (leaded phospher bronzes)
C61X00 C62X00 C63X00	Copper–aluminum alloys (aluminum bronzes)
C64X00 C65X00	Copper–silicon alloys (silicon bronzes)
C66X00 C67X00 C68X00 C69X00	Copper–zinc alloys (misc. brasses and bronzes)
C70X00 C71X00 C72X00	Copper–nickel alloys
C73X00 C74X00 C75X00 C76X00 C77X00 C78X00 C79X00	Copper–nickel–zinc alloys (nickel–silvers)
	Cast Alloys—Groups
C80X00	Copper alloys (99+ % copper)
C81X00 C82X00	High-copper alloys (beryllium copper)
C83X00	Copper–tin–zinc + copper–tin–zinc–lead alloys (red brasses and leaded red brasses)
C84X00	Semired brasses and leaded semired brasses
C85X00	Yellow brasses and leaded yellow brasses
C86X00	Manganese and leaded manganese bronze alloys
C87X00	Copper–zinc–silicon alloys (silicon bronzes and brasses)
C90X00 C91X00	Copper–tin alloys (tin bronzes)
C92X00	Copper–tin–lead alloy (leaded tin bronze)
C93X00	Copper–tin–lead alloy (high leaded tin bronze)

FIGURE 17-9 Copper and copper alloy designation system.

Copper has the highest thermal conductivity of all commercial metals and the comments made concerning thermal conductivity of aluminum apply to copper, to an even greater degree.

Copper has a relatively high coefficient of thermal expansion, approximately 50% higher than carbon steel, but lower than aluminum. One of the problems associated with copper alloys is the fact that some of them, such as aluminum bronze, have a coefficient of expansion over 50% greater than that of copper. This creates problems when making generalized statements about the different copper-based alloys.

The melting point of the different copper alloys varies over a relatively wide range, but is at least 1000 °F (538 °C) lower than carbon steel. Some of the copper alloys are *hot short*. This means that they become brittle at high temperatures. This is because some of the alloying elements form oxides and other compounds at the grain boundaries, embrittling the material.

Copper does not exhibit heat colors like steel and when it melts it is relatively fluid. Copper has the highest electrical conductivity of any of the commercial metals and this is a definite problem in the resistance welding processes.

All the copper alloys derive their strength from cold working. The heat of welding will anneal the copper in the heat-affected area adjacent to the weld and reduce the strength provided by cold working. This must be considered when welding high-strength joints.

There is one other problem associated with the copper alloys that contain zinc. Zinc has a relatively low boiling temperature, and the heat of an arc will tend to vaporize the zinc. The arc processes must be used with care for the alloys containing zinc.

The grouping of the copper alloys in Figure 17-9 is for convenience; however, there may be certain alloys within the grouping that are different from the others. In view of these, it is difficult to make generalized statements that apply to all the alloys in a particular grouping. For best results it is wise to know the exact composition of the alloy being welded. If it fits within a particular grouping, the recommended filler metal can be checked by referring to Figure 17-10, which gives the nominal composition of the copper alloy filler metals. The data shown here are for the filler metal, whether it is an electrode, a rod, or wire, or for brazing. Refer to AWS specifications A5.6, A5.7, and A5.8 for details. The composition of the filler material should be chosen to match the base metal as closely as possible.

The gas metal arc welding and the gas tungsten arc welding processes are the most popular for welding copper and copper alloys.

The gas tungsten arc welding process normally uses direct current electrode negative (straight polarity), but in some cases alternating current with high frequency is recommended. Gas tungsten arc welding is best for welding the thinner gauges of copper and copper alloys. It is also recommended for repairing copper alloy castings.

The gas metal arc welding process is used for welding thicker materials. It is faster, has a higher deposition rate, and usually results in less distortion. It can produce high-quality welds in all positions. It uses direct-

AWS Class	Nominal Composition in % Cu	Al	Fe	Mn	Ni	Si	Sn	Pb	Ti	Zn	Other
Cu	98	0.01	—	0.5	—	0.50	1.0	0.22	—	—	0.50
CuAl-Al	rem	6.0 to 9.0	—	—	—	0.10	—	0.02	—	0.20	0.50
CuAl-A2	rem	9.0 to 11.0	1.5	—	—	0.10	—	0.02	—	0.02	0.50
CuAl-B	rem	11.0 to 12.0	3.0 to 4.25	—	—	0.10	—	0.02	—	0.02	0.50
CuNi	rem	—	0.40 to 0.75	1.00	29	0.50	—	0.02	0.15 to 1.00	—	0.50
CuSi	rem	0.01	0.5	1.5	—	2.8 to 4.0	1.5	0.02	—	—	0.50
CuSi-A	94	0.01	0.5	1.5	—	2.8 to 4.0	1.5	0.02	—	1.5	0.50
CuSn-A	rem	0.01	—	—	—	—	4.0 to 6.0	0.02	—	—	0.50
CuSn-C	rem	0.01	—	—	—	—	7.0 to 9.0	0.02	—	—	0.50
CuZn-A	57 to 61	0.01	—	—	—	—	0.25 to 1.0	0.05	—	rem	0.50
CuZn B	56 to 60	0.01	0.25 to 1.2	0.01 to 0.50	0.2 to 0.8	0.04 to 0.15	0.8 to 1.1	0.05	—	rem	0.50
CuZn-C	56 to 60	0.01	0.25 to 1.2	0.01 to 0.50	—	0.04 to 0.15	0.8 to 1.1	0.05	—	rem	0.50
CuZn-D	46 to 50	0.01	—	—	9.0 to 11.0	0.04 to 0.25	—	0.05	—	rem	0.50

From AWS Specifications A5.6, A5.7, and A5.8.

AWS class filler metals may have the prefix letter E = Electrode, R = Rod, RB = Rod or Brazing, B = Brazing.

FIGURE 17-10 Composition of copper alloy filler metals.

current electrode positive, and the CV power source is recommended.

Copper

There are three basic groups in the C100 series of copper designations. The C10X is the oxygen-free type which has a copper analysis of 99.95% or higher.

The oxygen-free high-conductivity copper contains no oxygen and is not subjected to grain boundary migration. Adequate gas coverage should be employed to avoid oxygen of the air coming into contact with the molten metal. Welds should be made as quickly as possible since too much heat or slow welding can contribute to oxidation. The deoxidized coppers are preferred because of their freedom from embrittlement by hydrogen. Hydrogen embrittlement occurs when copper oxide is exposed to a reducing gas at high temperature. The hydrogen reduces the copper oxide to copper and water vapor. The entrapped high temperature water vapor or steam can create sufficient pressure to cause cracking. In common with all copper welding, preheat should be used and can run from 250 to 1000°F (121 to 538°C), depending on the mass involved.

The second subgroup are the tough pitch coppers, which have a copper composition of 99.88% or higher and some high copper alloys which have 96% or more copper. The ECu or RCu class filler metal is recommended.

The tough pitch electrolytic copper is difficult to weld because of the presence of copper oxide within the

material. During welding the copper oxide will migrate to the grain boundaries, at high temperatures, which reduces ductility and tensile strength. The gas-shielded processes are recommended since the welding area is more localized and the copper oxide is less able to migrate in appreciable quantities.

The third copper subgroup is the high-copper alloys which may contain deoxidizers such as phosphorus. The ECuSi filler wires are used with this material. The preheat temperatures needed to make the weld quickly apply to all three grades.

Copper-Zinc Alloys (Brasses)

These are the C2XX family of copper alloys. Within this group there are many different types of brasses. These alloys contain zinc, and zinc vaporization can be reduced by decreasing or eliminating preheat and by using lower welding currents. The various filler metals, copper-silicon, copper-tin and aluminum-bronze, can all be used.

For lighter sections argon shielding is used. For thicker sections preheat should be employed at approximately 400 °F (200 °C). Helium and helium gas mixtures are recommended. The weld joint should be opened up sufficiently to allow root penetration.

Copper-Zinc-Lead Alloys (Leaded Brasses)

The leaded alloys in this C3XX group are not suitable for welding since the lead will create excessive porosity and promote cracking in the weld area.

Copper-Zinc-Tin Alloys (Tin Brasses)

This is the C4XX subgroup. These are the yellow brasses and are generally welded with the CuA1-A2 aluminum bronze filler metal. The same comments made concerning the copper-zinc alloys apply here.

Copper-Tin Alloys (Phosphur Bronzes)

This is the C5XX series which also includes the leaded phosphur bronzes. Except for the leaded bronzes, both the gas metal arc and gas tungsten arc processes can be used with the normal recommendations concerning thickness. These alloys have a tendency to be hot short and they have high thermal conductivity. High current density and a high travel speed should be used. Helium is recommended for shielding with gas tungsten arc welding. The level of tin in the filler wire should be selected to match the tin in the base metal. Preheat should be used in the range 300 to 400 °F (150 to 200 °C). When groove angles are used wide angles should be used. To reduce stresses and distortion, hot peening of the weld deposit is recommended. The CuSn filler metal should be used with the higher amount of tin to match the higher amount of tin in the base metals. The leaded phosphur bronzes should not be welded.

Copper-Aluminum Alloys (Aluminum Bronzes)

These are a subgroup in the C6XX class representing the lower numbers. Both the gas metal arc and gas tungsten arc processes are used with the gas metal arc used for the heavier thicknesses. Filler metal should be the CuA1-A2 type. Argon-helium mixtures are recommended. Preheat is required only for the heavier thicknesses. Full-penetration welds are recommended.

Copper-Silicon Alloys (Silicon Bronzes)

This is also a subgroup of the C6XX series. Both gas metal arc and gas tungsten arc welding can be used for this family of copper alloys. This alloy is free of volatile alloying elements and has a lower conductivity than many of the others. Preheat is recommended for heavier thicknesses. The leaded grade in this class is not suitable for welding.

Copper-Nickel Alloys

These alloys are in the low C7XX class of alloys. Both gas metal arc and gas tungsten arc welding processes can be used for these alloys. The filler metal should be the CuNi 70/30 type. Argon is normally used but for heavy thicknesses argon and helium mixtures can be employed. Preheating is normally not used and the interpass temperatures should not be allowed to rise above 150 °F (65 °C).

Copper-Nickel-Zinc Alloys (Nickel-Silver)

These alloys are in the high C7XX class of alloys. These alloys are not normally arc welded and should be joined by brazing. This is because of the relatively high amount of zinc included in these compositions.

The analysis of cast alloys similar to wrought alloys would be welded the same way. The filler metal should be selected to most closely approximate the analysis of the base metal.

Figure 17-11 provides recommended welding conditions for both gas metal arc and gas tungsten arc welding of copper alloys. This is a summary of material just covered and is a starting point for establishing a welding procedure. Welding procedure schedules are provided for welding the different copper alloys with both

Material Type	Filler Metal	GTAW Shielding Gas	GTAW Welding Current	GTAW Electrode Type	GMAW Electrode Class	GMAW Shielding Gas	Notes
Copper* (E1xx)	RCu	Helium Argon or Mixture	DCEN AC-HF	EWTh-2	ECu	Argon plus helium	Preheat higher temp for thicker materials
Brasses* (C-2xx) (copper-zinc)	RCuZn-B RCuZn-C RCuZn-D	Argon Helium Mixture	DCEN AC-HF	EWTh-1	—	—	Preheat—open up joint—do not weld leaded types
Tin brasses* (C4xx)	RCuZn-A RCuZn-C	Argon Helium Mixtures	DCEN AC-HF	EWTh-1	ECuAl-A2	Argon plus Helium	Preheat—open up joint—higher temp for thicker materials.
Phosphor bronze (C5xx) (copper-tin)	RCuSn-A RCuSn-C RCuSn-D	Argon Helium Mixture	DCEN	EWTh-2	ECuSn-A ECuSn-C	Argon	Weld quickly hot short do not weld leaded types
Aluminum bronze (C61x, 62x and 63x) (copper aluminum)	RCuAl-A2 RCuAl-B	Argon Helium Mixture	AC-HF DCEN	EWTh-1	ECuAl-A1 ECuAl-A2 ECuAl-B	Argon	Relatively easy to weld
Silicon bronze (C64x and 65x) (copper-aluminum)	RCuSi-A	Argon	DCEN	EWTh-1	ECuSi	Argon	Relatively easy to weld. Do not weld leaded types
Copper nickel (C7xx)	RCuNi	Argon	DCEN	EWTh-1	ECuNi	Argon	Relatively easy to weld

*Preheat

FIGURE 17-11 Recommended welding condition for GMAW and GTAW of copper alloys.

gas tungsten arc welding and gas metal arc welding (Figures 17-12 and 17-13).

Other Welding Processes

Many welding processes can be used to join copper and copper alloys. Soldering is widely used for joining most of the copper alloys; however, the high aluminum content and aluminum–manganese bronzes are not readily soldered. Both corrosive and resin type fluxes are used for soldering copper. There is one precaution. Solders containing more than 1.0% antimony or more than 0.02% arsenic should not be used to solder the copper–zinc alloys. They will produce brittle joints or have poor bonding. The soldering process does not utilize sufficiently high heat to cause annealing of the copper base alloys.

Brazing is widely used. The copper–phosphorus filler material (BCuP) and some of the silver alloy (BAg) types are used. The copper phosphorus is much less expensive but is not used for copper alloys that contain more than 10% nickel. In addition, the copper–phosphorus alloy does not provide as high an electrical conductivity as the silver alloys.

Several of the other arc welding processes can be used. Plasma arc welding is becoming more popular for welding copper alloys. The same comments made concerning gas tungsten arc welding previously will apply. The submerged arc welding process has been used for copper alloy welding and overlaying. Specialized fluxes for copper alloys must be used.

The cold welding process is widely used on coppers; so are high-frequency welding and the electron and laser beam welding processes. Additional information for the welding of copper and copper alloys can be obtained from the various bulletins published by the Copper Development Association, Inc.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Tungsten Electrode Diameter in.	mm	Filler Rod Diameter in.	mm	Nozzle Size Inside Dia. in.	Shielding Gas Flow cfh	Welding Current Amps DCEN	No. of Passes	Travel Speed (per pass) ipm
16	0.063	1.6	Square Groove	1/16	1.6	1/16	1.6	3/8	20	100-150	1	10-12
16	0.063	1.6	Fillet	1/16	1.6	1/16	1.6	3/8	20	85-125	1	10-12
11	0.125	3.2	Square Groove	3/32	2.4	3/32	2.4	3/8	20	170-235	1	8-11
11	0.125	3.2	Fillet	3/32	2.4	3/32	2.4	3/8	20	115-165	1	10-12
3/16	0.187	4.7	Square Groove	1/8	3.2	1/8	3.2	5/8	35	185-255	1	8-12
3/16	0.187	4.7	Fillet	3/32	2.4	3/32	2.4	3/8	25	170-230	1	8-12
1/4	0.250	6.4	Fillet	1/8	3.2	1/8	3.2	1/2	40	220-275	1	7-10
1/4	0.250	6.4	Single Vee	1/8	3.2	1/8	3.2	1/2	40	220-275	2	7-10
1/4	0.250	6.4	Edge	1/8	3.2	1/8	3.2	1/2	25	160-225	1	7-10
1/4	0.250	6.4	Double Vee	1/8	3.2	1/8	3.2	1/2	20	180-220	3	8-12
3/8	0.375	9.5	Fillet	3/16	4.8	3/16	4.8	1/2	45	275-325	3	8-12
3/8	0.375	9.5	Single Vee	1/8	3.2	1/8	3.2	1/2	25	225-290	3	8-12
3/8	0.375	9.5	Double Vee	5/32	3.9	1/8	3.2	1/2	20	200-250	3	8-12
1/2	0.500	12.7	Fillet	1/4	6.4	1/4	6.4	5/8	45	370-500	4	8-12
1/2	0.500	12.7	Single Vee	1/8	3.2	1/8	3.2	1/2	30	280-330	7	7-10
1/2	0.500	12.7	Double Vee	5/32	3.9	1/8	3.2	1/2	30	180-250	4	7-10

1. Increase amperage 100% when backup is used.
2. Data is for flat position. Reduce amperage 10%-20% when welding in horizontal, vertical, or overhead position.
3. For tungsten electrodes: 1st choice 1% thoriated EWTh1; 2nd choice 2% thoriated EWTh2.
4. For copper use helium for shielding, however, a mixture of 75% He + 25% Argon is very popular on copper and some copper alloys. Argon is usually for bronzes.
5. Preheat 3/16" copper 200° F, 1/4" –300° F, 3/8" –500° F, Preheat '/4" and up –900° F.
6. Deoxidized copper and copper alloys use DCEN—aluminum bronze uses ACHF and argon for shielding.

FIGURE 17-12 Welding procedure schedules for GTAW of copper alloys.

FIGURE 17-13 Welding procedure schedules for GMAW of copper alloys.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Electrode Diameter in.	mm	Welding Power Current Amps DC	Arc Volt EP	Wire Feed Speed ipm	Shielding Gas Flow cfh	No. of Passes	Travel Speed (per pass) ipm
16	0.063	1.6	Deoxidized copper	3/64	1.2	150-170	22-24	210-220	35	1	20-23
14	0.078	1.9	Sq. groove & fillet	3/64	1.2	180-200	22-25	240-270	40	1	20-25
12	0.109	2.8	Sq. groove & fillet	3/64	1.2	200-230	23-27	270-290	40	1	20-25
11	0.125	3.2	Sq. groove & fillet	3/64	1.2	210-240	23-27	280-300	40	1	20-25
1/4	0.250	6.4	Sq. groove & fillet	1/16	1.6	380-410	23-29	260-270	40	1	12-15
1/4	0.250	6.4	Vee groove & fillet	1/16	1.6	300-330	23-27	190-210	40	1-3	14-17
3/8	0.375	9.2	Vee groove & fillet	1/16	1.6	340-360	24-28	220-240	40	1	12-15
1/2	0.500	12.7	Double Vee groove	3/32	2.4	400-440	24-30	270-290	50	2	8-10
3/4	0.750	19.0	Double Vee groove	3/32	2.4	420-460	24-30	290-315	50	3	7-9
1	1.000	25.4	Double Vee groove	3/32	2.4	420-460	24-30	270-300	50	4	7-9
1/8	0.125	1.2	Silicon Bronze	3/64	1.2	130-160	25-28	220-230	35	1	25-32
1/4	0.250	6.4	Fillet & Vee groove	1/16	1.6	270-290	27-30	170-190	40	1-3	26-33
1/4	0.250	6.4	Fillet & Vee groove	1/16	1.6	450-465	25-28	220-250	50	1	30-34
1/2	0.500	12.7	Fillet & Vee groove	1/16	1.6	335-350	27-30	180-200	50	3-5	15-20
1/8	0.125	3.2	Aluminum bronze	3/64	1.2	190-225	22-25	280-300	40	1	18-24
1/4	0.250	6.4	Vee groove & fillet	1/16	1.6	275-300	23-29	170-190	50	2	16-22
3/8	0.375	9.2	Vee groove & fillet	1/16	1.6	300-340	23-29	190-210	50	3-6	16-22
1/2	0.500	12.7	Double Vee groove	1/16	1.6	320-350	23-29	200-220	50	6-8	11-15
5/8	0.625	15.9	Double Vee groove	1/16	1.6	320-345	23-29	220-240	50	6-8	9-13
3/4	0.750	19.0	Double Vee groove	1/16	1.6	340-370	23-29	220-240	50	6-8	9-12

1 - If preheating is required, a range of 500 to 900° F may be used for aluminum, bronze, and deoxidized copper and 400 to 600° F on silicon bronze.
2 - Argon is normally used. If porosity is encountered, it can be eliminated by adding an equal amount of helium to the argon flow.
3 - Speeds and currents for fully automatic welding are approximately 15% higher.

17-3 MAGNESIUM-BASE ALLOYS

Magnesium is the lightest structural metal. It is approximately two-thirds as heavy as aluminum and one-fourth as heavy as steel. Magnesium alloys containing small amounts of aluminum, manganese, zinc, zirconium, etc., have strengths equaling that of mild steels. They can be rolled into plate, shapes, and strip. Magnesium can be cast, forged, fabricated, and machined. As a structural metal it is used in aircraft. It is used by the materials-moving industry for parts of machinery and for hand-power tools due to its strength to weight ratio. Magnesium can be welded by many of the arc and resistance welding processes, as well as by the oxyfuel gas welding process, and it can be brazed.

The more popular magnesium alloys are shown in Figure 17-14. This chart shows the ASTM designations per ASTM B275 and the UNS designation. Magnesium like aluminum is produced with different tempers. These are based on heat treatment and work hardening. They are listed following the alloy classification and use the prefix letter T followed by a number ranging from 1 to 10, the higher numbers indicating the higher hardness. The letter F is also used indicating as fabricated. The letter H is used to indicate the heat treat condition. The strength of a weld joint is lowered in base metal, in the work-hardened condition, as a result of recrystallization and grain growth in the heat-affected zone. This effect is minimized with gas metal arc welding because of the higher welding speed utilized. This is not a factor in the base metals that are welded in the soft condition.

Welding Magnesium Alloys

Magnesium possesses properties that make welding it different than the welding of steels. Many of these are the same as for aluminum. These are:

1. Magnesium oxide surface coating
2. High thermal conductivity
3. Relatively high thermal expansion coefficient
4. Relatively low melting temperature
5. The absence of color change as temperature approaches the melting point

The normal metallurgical factors that apply to other metals apply to magnesium as well.

Magnesium is a very active metal and the rate of oxidation increases as the temperature is increased. The melting point of magnesium is very close to that of aluminum, but the melting point of the oxide is very high. In view of this, the oxide coating must be removed.

Magnesium has high thermal heat conductivity and a high coefficient of thermal expansion. The thermal conductivity is not as high as aluminum but the coefficient of thermal expansion is very nearly the same. The ab-

FIGURE 17-14 Composition of magnesium alloys.

ASTM Alloy	Nominal Composition—Percent Aluminum	Manganese	Zinc	Zirconium	Rare earths	Thorium	Magnesium
			sand and permanent mold castings				
AZ92A	9.0	0.15	2.0	–	–	–	Balance
AZ63A	6.9	0.25	3.0	–	–	–	Balance
AZ81A	7.6	0.13 min.	0.7	–	–	–	Balance
AZ91C	8.7	0.20	0.7	–	–	–	Balance
EK30A	–	–	–	0.35	3.0	–	Balance
EK41A	–	–	–	0.6	4.0	–	Balance
EZ33A	–	–	2.7	0.7	3.0	–	Balance
HK31A	–	–	–	0.7	–	3.0	Balance
HZ32A	–	–	2.1	0.7	–	3.0	Balance
			die castings				
AZ91A AZ91B	9.0	0.20	0.6	–	–	–	Balance
			extrusions				
AZ31B AZ31C	3.0	0.45	1.0	–	–	–	Balance
AZ61A	6.5	0.30	1.0	–	–	–	Balance
M1A	–	1.50	–	–	–	–	Balance
AZ80A	8.5	0.25	0.5	–	–	–	Balance
ZK60A	–	–	5.7	0.55	–	–	Balance
			sheet and plate				
AZ31B	3.0	0.45	1.0	–	–	–	Balance
HK31A	–	–	–	0.7	–	3.0	Balance

Per ASTM B275 magnesium alloys (abridged).

AWS Classification	Mg	Al	Be	Mn	Zn	Zi	Rare earth	Cu	Fe	Ni	Si
					NOMINAL COMPOSITION %						
AZ61A	rem	5.8 to 7.2	0.0002 to 0.0008	0.15	0.40 to 1.5	–	–	0.05	0.005	0.005	0.05
AZ101A	rem	9.5	0.0002 to 0.008	0.13	0.75	–	–	0.05	0.005	0.005	0.05
AZ92A	rem	8.3 to 9.7	0.0002 to 0.0008	0.15	1.75	–	–	0.05	0.005	0.005	0.05
EZ33A	rem	–	–	–	2.0 to 3.1	0.45 to 1.0	2.5 to 4.0	–	–	–	–

Use suffix letter E = Electrode or R = Rod.

FIGURE 17-15 Composition of magnesium filler metals per AWS A5.19.

FIGURE 17-16 Guide to the choice of filler metal for welding magnesium. (From Ref. 6.)

Base Alloy / Filler Alloy	AM100A	AZ10A	AZ31B&C	AZ61A	AZ63A	AZ80A	AZ81A	AZ91C	AZ92A	EK41A	EZ33A
AM100A	1. AZ92A 2. AZ101										
AZ10A	AZ92A	1. AZ61A 2. AZ32A									
AZ31B&C	AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A								
AZ61A	AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A							
AZ63A	X	X	X	X	AZ92A						
AZ30A	AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	X	1. AZ61A 2. AZ92A					
AZ81A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	1. AZ92A 2. AZ101				
AZ91C	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	1. AZ92A 2. AZ101			
AZ92A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ101		
EK41A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ92A	EZ33A	
EZ33A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ92A	EZ33A	EZ33A
HK31A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ92A	EZ33A	EZ33A
HM21A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ92A	EZ33A	EZ33A
HM31A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ92A	EZ33A	EZ33A
HZ32A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ92A	EZ33A	EZ33A
K1A	AZ92A	AZ92A	AZ92A	AZ92A	X	AZ92A	AZ92A	AZ92A	AZ92A	EZ33A	EZ33A
LA141A	0	0	E233A	X	X	X	X	X	X	0	0
M1A MG1	AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	X	1. AZ61A 2. AZ92A	AZ92A	AZ92A	AZ92A	AZ92A	AZ92A
QE22A	0	0	0	0	X	0	0	0	0	EZ33A	EZ33A
ZE10A	AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	X	1. AZ61A 2. AZ92A	AZ92A	AZ92A	AZ92A	1. EZ33A 2. AZ92A	1. EZ33A 2. AZ92A
ZE41A	0	0	0	0	X	0	0	0	0	EZ33A	EZ33A
ZX21A	AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	1. AZ61A 2. AZ92A	X	1. AZ61A 2. AZ92A	AZ92A	AZ92A	AZ92A	AZ92A	AZ92A
ZH62A ZK51A ZK60A ZK61A	X	X	X	X	X	X	X	X	X	X	X

sence of color change is not too important with the arc welding processes.

The welds produced between similar alloys will develop the full strength of the base metals; however, the strength of the heat-affected zone may be reduced slightly. In all magnesium alloys the solidification range increases and the melting point and the thermal expansion decrease as the alloy content increases. Aluminum added as an alloy up to 10% improves weldability since it tends to refine the weld grain structure. Zinc of more than 1% increases hot shortness which can result in weld cracking. The high-zinc alloys are not recommended for arc welding because of their cracking tendencies. Magnesium, containing small amounts of thorium, possesses excellent welding qualities and freedom from cracking. Weldments of these alloys do not require stress relieving.

Certain magnesium alloys are subject to stress corrosion. Weldments subjected to corrosive attack over a period of time may crack adjacent to welds if the residual stresses are not removed. For weldments intended for this type of service stress relieving is required.

Gas tungsten arc welding and gas metal arc welding are recommended for joining magnesium. Gas tungsten arc is recommended for thinner materials and gas metal arc is recommended for thicker materials; however, there is considerable overlap.

The filler metal alloys used for joining magnesium are shown in Figure 17-15. It is based on AWS specification A5.19. The composition of filler metals should match the composition of the base materials; however, there are many cases in which this cannot be done. In all cases the recommendations shown in Figure 17-16 should be used.

FIGURE 17-16 (*cont.*)

HK31A	HM21A	HM31A	HZ32A	K1A	LA141A	M1A MG1	QE22A	ZE10A	ZE41A	ZX21A	ZH62A ZK51A ZK60A ZK61A
EZ33A											
EZ33A	EZ33A										
EZ33A	EZ33A	EZ33A									
EZ33A	EZ33A	EZ33A	EZ33A								
EZ33A	EZ33A	EZ33A	EZ33A	EZ33A							
0	EZ33A	0	0	0	1. LA141A 2. EZ33A						
AZ92A	AZ92A	AZ92A	AZ92A	AZ92A	0	1. AZ61A 2. AZ92A					
EZ33A	EZ33A	EZ33A	EZ33A	EZ33A	EZ33A	0	EZ33A				
1. EZ33A 2. AZ92A	1. EZ33A 2. AZ92A	1. EZ33A 2. AZ92A	1. EZ33A 2. AZ92A	1. EZ33A 2. AZ92A	EZ33A	1. AZ61A 2. AZ92A	1. EZ33A 2. AZ92A	1. AZ61A 2. AZ92A			
EZ33A	EZ33A	EZ33A	EZ33A	EZ33A	0	0	EZ33A	0	EZ33A		
AZ92A	AZ92A	AZ92A	AZ92A	AZ92A	0	1. AZ61A 2. AZ92A	AZ92A	1. AZ61A 2. AZ92A	AZ92A	1. AZ61A 2. AZ92A	
X	X	X	X	X	X	X	X	X	X	X	EZ33A

Gas Tungsten Arc Welding

Welding procedure schedules for gas tungsten arc welding of magnesium are given in Figure 17-17. All the precautions mentioned for welding aluminum should be observed. A short arc should be used and the torch should have a slight leading travel angle. The cold wire filler metal should be brought in as near to horizontal as possible (on flat work). The filler wire is added to the leading edge of the weld puddle. High-frequency current should be used for starting the direct current arc. With alternating current, high frequency should be used continuously. Runoff tabs are recommended for welding any except the thinner materials. Uniform travel speed and weld beads are recommended. The shielding gas is normally argon. However, a mixture of 75% helium plus 25% argon is used for thicker materials. For heavy thicknesses 100% helium can be used; more helium is required than argon to do the same job.

Direct current with electrode positive can be used but only for machine or automatic welding. In this case, materials must be perfectly clean prior to welding. Additional details are given by the welding procedure schedule.

Gas Metal Arc Welding of Magnesium

Gas metal arc welding is used for the medium to thicker sections. Special high-speed gear ratios are usually required in the wire feeders since the magnesium electrode wire has an extremely high meltoff rate. The normal wire feeder and power supply used for aluminum welding will be suitable for welding magnesium. The different types of arc transfer can be obtained when welding magnesium. This is primarily a matter of current level or current density and voltage setting. The short-circuiting transfer and the spray transfer are recommended. Argon is usually used for gas metal arc welding of aluminum; however, argon-helium mixtures can be used. In general, the spray transfer should be used on material $\frac{3}{16}$ in. and thicker and the short-circuiting arc used for thinner metals. Figure 17-18 provides welding procedure schedules.

Welding Problems

Magnesium is usually delivered with an oil preservative. The oil must be removed with a solvent and the material should be cleaned either by mechanical or chemical methods. Scraping and brushing is often used and a stainless steel brush should be used.

If cracking persists in magnesium welds, check the welding technique. Craters must always be filled and runoff tabs should be used. Preheating is recommended for complex weldments. Preheating in the range 200 to 400 °F (93 to 204 °C) should be employed. Stress relieving is recommended when the weldment is exposed to corrosion.

Other Welding Processes

Resistance welding can be used for welding magnesium, including spot welding, seam welding, and flash welding. Magnesium can also be joined by brazing. In all cases, brazing flux is required and the flux residue must be com-

FIGURE 17-17 Welding procedure schedule for GTAW of magnesium.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Tungsten Electrode Diameter in.	mm	Filler Rod Diameter in.	mm	Nozzle Size Inside Dia. in.	Shielding Gas Flow cfh	Welding Current Amps DCEN	No. of Passes	Travel Speed (per pass) ipm
20	0.038	0.9	Square Groove	1/16	1.6	3/32	2.4	1/4	15	25-40	1	20
20	0.038	0.9	Fillet	1/16	1.6	3/32	2.4	1/4	15	30-45	1	20
16	0.063	1.6	Square Groove	1/16	1.6	3/32	2.4	1/4	15	45-60	1	20
16	0.063	1.6	Fillet	1/16	1.6	3/32	2.4	1/4	15	45-60	1	20
14	0.078	1.9	Square Groove	1/16	1.6	3/32	2.4	1/4	15	60-75	1	17
14	0.078	1.9	Fillet	1/16	1.6	3/32	2.4	1/4	15	60-75	1	17
12	0.109	2.8	Square Groove	3/32	2.4	1/8	3.2	5/16	15	80-100	1	17
12	0.109	2.8	Fillet	3/32	2.4	1/8	3.2	5/16	15	80-100	1	17
11	0.125	3.2	Square Groove	3/32	2.4	1/8	3.2	5/16	25	95-115	1	17
11	0.125	3.2	Fillet	3/32	2.4	1/8	3.2	5/16	25	95-115	1	17
3/16	0.187	4.7	Vee Groove	1/8	3.2	1/8	3.2	3/8	25	95-115	2	26
1/4	0.250	6.4	Vee Groove	1/8	3.2	3/16	4.8	1/2	25	110-130	2	24
3/8	0.375	9.5	Vee Groove	1/8	3.2	3/16	4.8	1/2	30	135-165	2	20

(1) Increase amperage when backup is used.
(2) Data is for flat position. Reduce amperage 10%-20% when welding in horizontal, verticla or overhead positions.
(3) Tungsten electrode: 1st choice zirconated EWZr; 2nd choice pure tungsten EWP.
(4) Select filler metal in accordance to selection chart.
(5) Shielding gas is normally argon. A mixture of 75% helium + 25% argon is used for heavier thickness. For heavy thickness 100% helium is used. Gas flow rates for helium are approximately twice those used for argon.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Electrode Diameter in.	mm	WELDING POWER Current Amps DC	Arc Volt EP	Wire Feed Speed ipm	Shielding Gas Flow cfh	No. of Passes	Travel Speed (per pass) ipm
0.025	–	–	Sq. groove & fillet	0.040	1.0	26-27	13-16	180	40-60	1	24-36
0.040	–	–	Sq. groove & fillet	0.040	1.0	35-50	13-16	250-340	40-60	1	24-36
0.063	1/16	1.6	Sq. groove & fillet	0.063	1.6	60-75	13-16	140-170	40-60	1	24-36
0.090	3/32	2.4	Sq. groove & fillet	0.063	1.6	95-125	13-16	210-280	40-60	1	24-36
0.125	1/8	3.2	Sq. groove & fillet	0.094	2.4	110-135	13-16	100-130	40-60	1	24-36
0.160	5/32	3.9	Sq. groove & fillet	0.094	2.4	135-140	13-16	130-140	40-60	1	24-36
0.190	3/16	4.8	Vee groove & fillet	0.094	2.4	175-205	13-16	160-190	40-60	2	24-36
0.250	1/4	6.4	Vee groove & fillet	0.063	1.6	240-290	24-30	550-660	50-80	2	24-36
0.375	3/8	9.5	Vee groove & fillet	0.094	2.4	320-350	24-30	350-385	50-80	2	24-36
0.500	1/2	12.7	Vee groove & fillet	0.094	2.4	350-420	24-30	385-415	50-80	2	24-36
1.00	1	25.4	Vee groove & fillet	0.094	2.4	350-420	24-30	385-415	50-80	4	24-36

Note: Values are for flat position

(1) For groove and fillet welds—material thickness also indicates fillet weld size. Use vee groove for 1/4" and thicker.

(2) Shielding gas is argon or for heavier thicknesses use helium-argon mixtures.

(3) Above 200 amps and 20 volts, metal transfer is spray type—below 200 amps and 20 volts, metal transfer is short circuiting type.

FIGURE 17-18 Welding procedure schedule for GMAW of magnesium.

pletely removed from the finished part. Soldering is not too popular since the strength of the joint is relatively low.

Magnesium can be stud welded, gas welded, and plasma welded. Finely divided pieces of magnesium such as shavings, filings, and so on, should not be in the welding area since they will burn. Magnesium castings or wrought materials do not create a safety hazard since the possibility of fire caused by welding on these sections is very remote. The producers of magnesium provide additional data for welding magnesium.[6]

17-4 NICKEL-BASE ALLOYS

Nickel and the high-nickel alloys are commonly used when corrosion resistance is required. They are used in the chemical industry and the food industry. Nickel and nickel alloys are also widely used as filler metals for joining dissimilar materials and cast iron.

There is no standard specification or designation system for the nickel alloys. In general, they are identified by trademark names and suffix numbers. The trademark names are:

- *Monel:* a nickel–copper alloy
- *Inconel:* a high-nickel–chromium alloy with iron
- *Incoloy:* a nickel–iron–chromium alloy
- *Hastealloy:* a nickel–molybdenum–iron alloy

There are other nickel alloys. The trademark names of the International Nickel Company or the Huntington Alloy Products Division will be used. The more common nickel alloys are shown in Figure 17-19, which also shows UNS numbers.

When welding, the nickel alloys can be treated much in the same manner as austenitic stainless steels with a few exceptions. These exceptions are:

1. The nickel alloys will acquire a surface oxide coating which melts at a temperature approximately 1000 °F (538 °C) above the melting point of the base metal.
2. The nickel alloys are susceptible to embrittlement at welding temperatures by lead, sulfur, phosphorus, and some low-temperature metals and alloys.
3. Weld penetration is less than expected with other metals.

When adjustments are made for these three factors the welding procedures used for the nickel alloys can be the same as those used for stainless steel. This is because the melting point, the coefficient of thermal expansion, and the thermal conductivity are similar to austenistic stainless steel.

It is necessary that each of these precautions be considered. The surface oxide should be completely removed from the joint area by grinding, abrasive blasting, machining, or by chemical means. When chemical etches are used they must be completely removed by rinsing prior to welding. The oxide which melts at temperatures above the melting point of the base metal may enter the weld as a foreign material, or impurity, and will greatly reduce the strength and ductility of the weld.

The problem of embrittlement at welding temperatures also means that the weld surface must be absolutely clean. Paints, marking crayons, grease, oil, machining lubricants, and cutting oils may all contain the ingredients which will cause embrittlement. They must be completely removed from the weld area to avoid embrittlement.

Alloy Designation	UNS Number	Nominal Chemical Composition %											
		Ni	C	Mn	Fe	S	Si	Cu	Cr	Al	Ti	Cb[a]	Others
Nickel 200	NO2200	99.5[b]	0.08	0.18	0.2	0.005	0.18	0.13	–	–	–	–	–
Nickel 201	NO2201	99.5[b]	0.01	0.18	0.2	0.005	0.18	0.13	–	–	–	–	–
Nickel 205	NO2205	99.5[b]	0.08	0.18	0.10	0.004	0.08	0.08	–	–	0.03	–	Mg 0.05
Nickel 211	–	95.0[b]	0.10	4.75	0.38	0.008	0.08	0.13	–	–	–	–	–
Nickel 220	NO2220	99.5[b]	0.04	0.10	0.05	0.004	0.03	0.05	–	–	0.03	–	Mg 0.05
Nickel 230	NO2230	99.5[b]	0.05	0.08	0.05	0.004	0.02	0.05	–	–	0.003	–	Mg 0.06
Nickel 270	NO2270	99.98	0.01	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	–	<0.001	–	Mg <0.001, Co<0.001
Duranickel alloy 301	–	96.5[b]	0.15	0.25	0.30	0.005	0.5	0.13	–	4.38	0.63	–	–
Permanickel alloy 300	–	98.5[b]	0.20	0.25	0.30	0.005	0.18	0.13	–	–	0.40	–	Mg 0.35
Monel alloy 400	NO4400	66.5[b]	0.15	1.0	1.25	0.012	0.25	31.5	–	–	–	–	–
Monel alloy 401	–	42.5[b]	0.05	1.6	0.38	0.008	0.13	Bal.	–	–	–	–	–
Monel alloy 404	NO4404	54.5[b]	0.08	0.05	0.25	0.012	0.05	44.0	–	0.03	–	–	–
Monel alloy R-405	NO4405	66.5[b]	0.15	1.0	1.25	0.043	0.25	31.5	–	–	–	–	–
Monel alloy K-500	NO5500	66.5[b]	0.13	0.75	1.00	0.005	0.25	29.5	–	2.73	0.60	–	–
Monel alloy 502	NO5502	66.5[b]	0.05	0.75	1.00	0.005	0.25	28.0	–	3.00	0.25	–	–
Inconel alloy 600	NO6600	76.0[b]	0.08	0.5	8.0	0.008	0.25	0.25	15.5	–	–	–	–
Inconel alloy 601	NO6601	60.5	0.05	0.5	14.1	0.007	0.25	0.50	23.0	1.35	–	–	–
Inconel alloy 617	–	54.0	0.07	–	–	–	–	–	22.0	1.0	–	–	Co 12.5, Mo 9.0
Inconel alloy 625	NO6625	61.0[b]	0.05	0.25	2.5	0.008	0.25	–	21.5	0.2	0.2	3.65	Mo 9.0
Inconel alloy 671	–	Bal.	0.05	–	–	–	–	–	48.0	–	0.35	–	–
Inconel alloy 702	NO7702	79.5[b]	0.05	0.50	1.0	0.005	0.35	0.25	15.5	3.25	0.63	–	–
Inconel alloy 706	NO9706	41.5	0.03	0.18	40.0	0.008	0.18	0.15	16.0	0.20	1.75	2.9	–
Inconel alloy 718	NO7718	52.5	0.04	0.18	18.5	0.008	0.18	0.15	19.0	0.50	0.90	5.13	Mo 3.05
Inconel alloy 721	–	71.0[b]	0.04	2.25	6.5	0.005	0.08	0.10	16.0	–	3.05	–	–
Inconel alloy 722	NO7722	75.0[b]	0.04	0.50	7.0	0.005	0.35	0.25	15.5	0.70	2.38	–	–
Inconel alloy X-750	NO7750	73.0[b]	0.04	0.50	7.0	0.005	0.25	0.25	15.5	0.70	2.50	0.95	–
Inconel alloy 751	–	72.5[b]	0.05	0.5	7.0	0.005	0.25	0.25	15.5	1.20	2.30	0.95	–
Incoloy alloy 800	NO8800	32.5	0.05	0.75	46.0	0.008	0.50	0.38	21.0	0.38	0.38	–	–
Incoloy alloy 801	NO8801	32.0	0.05	0.75	44.5	0.008	0.50	0.25	20.5	–	1.13	–	–
Incoloy alloy 802	–	32.5	0.35	0.75	46.0	0.008	0.38	–	21.0	0.58	0.75	–	–
Incoloy alloy 804	–	41.0	0.05	0.75	25.4	0.008	0.38	0.25	29.5	0.30	0.60	–	–
Incoloy alloy 825	NO8825	42.0	0.03	0.50	30.0	0.015	0.25	2.25	21.5	0.10	0.90	-	Mo 3.0
Ni-span-C alloy 902	NO9902	42.25	0.03	0.40	48.5	0.02	0.50	0.05	5.33	0.55	2.58	–	–

[a]Cobalt included.
[b]Not for specification purposes.

FIGURE 17-19 Composition of nickels and nickel alloys.

AWS Class	UNS Number	Trade Name	Nominal Chemical Composition %										
			Ni	C	Mn	Fe	S	Si	Cu	Cr	Al	Ti	Cb	Mo
ERNi-3	NO2061	Nickel 61	96.0	0.06	0.30	0.10	0.005	0.40	0.02	—	—	3.0	—	—
ENi-1	—	Nickel 141	96.0	0.03	0.30	0.05	0.005	0.60	0.03	—	0.25	2.5	—	—
ERNiCu-7	—	Monel 60	65.0	0.03	3.5	0.20	0.005	1.00	27.0	—	—	2.2	—	—
ERNiCu-8	—	Monel 64	65.0	0.15	0.60	1.00	0.005	0.15	30.0	—	2.8	0.5	—	—
ERCuNi	—	Monel 67	31.0	0.02	0.75	0.50	0.005	0.10	67.5	—	—	0.30	—	—
ENiCuAl-1	—	Monel 134	64.0	0.20	2.50	1.00	0.005	0.30	30.0	—	1.8	0.75	—	—
ECuNi	—	Monel 187	32.0	0.02	2.00	0.60	0.01	0.15	65.0	—	—	—	—	—
ENiCu-2	—	Monel 190	65.0	0.01	3.10	0.30	0.007	0.75	30.5	—	0.15	0.55	—	—
ERNiCrFe-5	NO6062	Inconel 62	74.0	0.02	0.10	7.50	0.005	0.10	0.03	16.0	—	—	2.25	—
ERNiCrFe-7	NO7069	Inconel 69	73.0	0.04	0.55	6.50	0.007	0.30	0.05	15.2	0.70	2.5	0.85	—
ERNiCr-3	NO6082	Inconel 82	72.0	0.02	3.00	1.00	0.007	0.20	0.04	20.0	—	0.55	2.55	—
ERNiCrFe-6	NO7092	Inconel 92	71.0	0.03	2.30	6.60	0.007	0.10	0.04	16.4	—	3.2	—	—
—	—	Inconel 601	60.5	0.05	0.50	14.1	0.007	0.25	0.50	23.0	1.35	—	—	—
—	—	Inconel 625	61.0	0.05	0.25	2.5	0.008	0.25	—	21.5	0.2	0.2	3.65	9.0
—	—	Inconel 718	52.5	0.04	0.20	18.5	0.007	0.30	0.07	18.6	0.40	0.90	5.0	3.1
—	—	Inconel 112	61.0	0.05	0.3	4.0	0.010	0.40	—	21.5	—	—	3.6	9.0
ENiCrFe-1	NO6132	Inconel 132	73.0	0.04	0.75	8.5	0.006	0.20	0.04	15.0	—	—	2.1	—
ENiCrFe-3	—	Inconel 182	67.0	0.05	7.75	7.5	0.008	0.50	0.10	14.0	—	0.40	1.75	—
ENiCrFe-2	—	Inco-weld A	70.0	0.03	2.0	9.0	0.008	0.30	0.06	15.0	—	—	2.0	1.5
—	—	Inco-weld B	70.0	0.13	2.0	9.0	0.008	0.30	0.06	15.0	—	—	2.5	2.0
—	NO8065	Incoloy 65	42.0	0.03	0.70	30.0	0.007	0.30	1.70	21.0	—	1.0	—	3.0
—	—	Incoloy 135	36.0	0.05	2.00	26.0	0.008	0.40	1.80	29.0	—	—	—	3.75
ENi-C1	—	Ni-rod	95.0	1.00	0.20	3.0	0.005	0.70	0.10	—	—	—	—	—
ENiFe-C1	—	Ni-rod 55	53.0	1.50	0.30	45.0	0.005	0.50	0.10	—	—	—	—	—

[a]E, electrode; R, Rod.
Source: From AWS specifications A5.6, A5.7, A5.11, A5.14 and A5.15.

FIGURE 17-20 **Composition of nickel alloy filler metals.**

Alloy Designation	Electrode Inco Name	Electrode AWS–Spec	Rod Inco Name	Rod AWS–Spec
Nickel 200	141	ENi-1	61	ERNi-3
Nickel 201	141	ENi-1	61	ERNi-3
Monel alloy 400	190	ENiCu-2	60	ERNiCu-7
Monel alloy 404	190	ENiCu-2	60	ERNiCu-7
Monel alloy K-500	190*	ENiCu-2	60*	ERNiCu-7
Monel alloy 502	190*	ENiCu-2	60*	ERNiCu-7
Inconel alloy 600	132 (182)	ENiCrFe-1	62 (82)	ERNiCrFe-5
Inconel alloy 601	132 (182)	ENiCrFe-1	601 (82)	ERNiCrFe-5
Inconel alloy 625	112	–	625	–
Inconel alloy 706	N.A.	–	718	–
Inconel alloy 718	N.A.	–	718	–
Inconel alloy 722	N.A.	–	69	ERNiCrFe-7
Inconel alloy X-750	N.A.	–	69	ERNiCrFe-7
Incoloy alloy 800	182 (A)	ENiCrFe-3	82 (625)	ERNiCr-3
Incoloy alloy 801	182 (A)	ENiCrFe-3	82 (625)	ERNiCr-3
Incoloy alloy 825	135 (112)	–	65 (625)	–

Note: Electrodes are covered electrode for SMAW. Rods are solid bare for GTAW, GMAW, and SAW.
*will not age harden
N.A.—not available—use GTAW only

FIGURE 17-21 Guide for selecting filler metal for welding nickel alloys.

With respect to the minimum penetration, it is necessary to increase the opening of groove angles and to provide adequate root openings when full-penetration welds are used. The bevel or groove angles should be increased to approximately 40° over those used for carbon steel.

Almost all the welding processes can be used for welding the nickel alloys. In addition, they can be joined by brazing and soldering. The filler metals to be used for joining nickel alloys are shown in Figure 17-20. These are based on AWS filler metal specifications A5.11, A5.14, and A5.15 and include covered electrodes as well as bare solid wire for gas metal arc welding or for cold wire with other processes. The recommended filler metals for joining different alloys are shown in Figure 17-21.

Welding Nickel Alloys

The most popular processes for welding nickel alloys are shielded metal arc welding, gas tungsten arc welding, and gas metal arc welding. When shielded metal arc welding is used the procedures are essentially the same as those used for stainless steel welding.

The welding procedure schedule for using gas tungsten arc welding is shown in Figure 17-22. The welding procedure schedule for gas metal arc welding is shown in Figure 17-23. This procedure information on these tables will provide starting points for developing the welding procedures. The submerged arc welding process is used with proprietary fluxes manufactured by the nickel producer.

FIGURE 17-22 Welding procedure schedules for GTAW of nickel alloys.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Tungsten Electrode Diameter in.	mm	Filler Rod Diameter in.	mm	Nozzle Size Inside Dia. in.	Shielding Gas Flow cfh	Welding Current Amps DCEN	No. of Passes	Travel Speed (per pass) ipm
24	0.024	0.6	Sq. groove & fillet	1/16	1.6	None		3/8	15	8-10	1	8
16	0.063	1.6	Sq. groove & fillet	3/32	2.4	1/16	1.6	1/2	18	25-45	1	8
1/8	0.125	3.2	Sq. groove & fillet	1/8	3.2	3/32	2.4	1/2	25	125-175	1	11
1/4	0.25	6.4	Vee groove & fillet	1/8	3.2	1/8	3.2	1/2	30	125-175	2	8

1 - Tungsten used, 1st choice 2% thoriated EWTh2—2nd choice 1% thoriated EWTh1.
2 - Adequate gas shielding is a must not only for the arc but also heated metal. Backing gas is recommended at all times. A trailing gas shield is also recommended. Argon is preferred but for higher heat input on thicker material use Argon-Helium mixture.
3 - Data is for flat position. Reduce amperage 10% to 20% when welding is horizontal, vertical, or overhead position.

Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Electrode Diameter in.	mm	WELDING POWER Current Amps DC	Arc Volt EP	Wire Feed Speed ipm	Shielding Gas Flow cfh	No. of Passes	Travel Speed (per pass) ipm
1/16	0.062	1.6	Sq. groove & fillet	3/64	1.2	200-250	23-27	200-250	50	1	55-65
1/8	0.125	3.2	Sq. groove & fillet	1/16	1.6	290-340	25-35	150-175	60	1	30-35
1/4	0.250	6.4	Double Vee & fillet	1/16	1.6	300-350	28-38	170-200	80	3	20-25

1 - Use 50% helium and 50% argon for thin metal and 100% helium for thick—higher voltage is for helium.
2 - Increase amperage 10-20% when backup is used.
Data is for flat position. Reduce current 10-20% for other positions.

FIGURE 17-23 Welding procedure schedules for GMAW of nickel alloys.

No postweld heat treatment is required to maintain or restore corrosion resistance of the nickel alloys. Heat treatment is required for precipitating hardening alloys and stress relief may be required to meet certain specifications to avoid stress corrosion cracking in applications involving hydrofluoric acid vapors or caustic solutions. Additional welding information is available from the producers of the base materials.[7]

17-5 REACTIVE AND REFRACTORY METALS

The reactive and refractory metals were originally used in the aerospace industry and are now being welded for more and more requirements. These metals share many common welding problems and are, therefore, grouped together in this section. Reactive metals have a strong affinity for oxygen and nitrogen at elevated temperatures. At lower temperatures they are highly resistant to corrosion. Refractory metals have extremely high melting points. They may also exhibit some of the same characteristics of reactive metals.

The reactive metals are:

- Zirconium
- Titanium
- Beryllium

The refractory metals are:

- Tungsten
- Molybdenum
- Tantalum
- Columbium (niobium)

A summary of the physical properties of these metals is given in Figure 17-24. The refractory metals all have relatively high density, and thermal conductivity. The reactive metals have lower melting points, lower densities, and except for zirconium, have higher coefficients of thermal expansion.

The reactive metals are becoming increasingly important because of their use in nuclear and space technology. They are considered in the difficult-to-weld category. These metals have a high affinity for oxygen and other gases at elevated temperatures. They cannot be welded with any process that utilizes fluxes, or where heated metal is exposed to the atmosphere. Minor amounts of impurities cause these metals to become brittle.

Most of these metals have the characteristic known as the *ductile-brittle* transition. This refers to a temperature at which the metal breaks in a brittle manner rather than in a ductile fashion. The recrystalization of the metal during welding can raise the transition temperature. Contamination during the high temperature period and im-

FIGURE 17-24 Physical properties of the refractory and reactive metals.

Element	Crystal Structure	Melting Point F°	C°	Density lb/ft^3	gr/cc	Thermal Conductivity cal/cm^2/cm/sec/°C	Thermal Expansion micro-in./in./°F
W-Tungsten	BCC	6170	3410	1190	19.3	0.397	2.55
Ta-Tantalum	BCC	5425	2996	1035	16.6	0.130	3.6
Mo-Molybdenum	BCC	4730	2610	650	9.0	0.34	2.7
Cb-Columbium	BCC	4474	2567	524	8.4	0.125	4.06
Zr-Zirconium	HCP	3366	1796	*402	6.4	—	3.2
Be-Beryllium	HCP	2332	1377	*114	1.8	0.35	6.4
Ti-Titanium	HCP	3035	1668	281	4.5	—	4.67

purities can raise the transition temperature so that the material is brittle at room temperatures. If contamination occurs so that transition temperature is raised sufficiently it will make the weldment worthless. Gas contamination can occur at temperatures below the melting point of the metal. These temperatures range from 700°F (371°C) up to 1000°F (538°C).

At room temperature the reactive metals have an impervious oxide coating that resists further reaction with air. The oxide coatings melt at temperatures considerably higher than the melting point of the base metal. The oxidized coating may enter molten weld metal and create discontinuities which reduce the strength and ductility of the weld. Of the three reactive metals, titanium is the most popular and is routinely welded with special precautions.

All the refractory metals incur internal contamination or surface errosion when exposed to the air at elevated temperatures. Molybdenum has an extremely high rate of oxidation at high temperatures above 1500°F (816°C). Tungsten is much the same. Tantalum and columbium form pentoxides that are not volatile below 25°F (−3.9°C), but these provide little protection because they are nonadherent. Molybdenum and tungsten both become embrittled when a minute amount of oxygen or nitrogen is absorbed. Columbium and tantalum can withstand larger amounts of oxygen and nitrogen.

Titanium can withstand much more oxygen or nitrogen before becoming embrittled; however, small amounts of hydrogen will cause embrittlement. Zirconium can withstand about as much oxygen but much less nitrogen or hydrogen. Beryllium is similar to zirconium in this regard.

Welding Refractory Metals

These metals must be perfectly clean prior to welding and they must be welded in such a manner that air does not come into contact with the heated material. Cleaning is usually done with chemicals. A water rinse is necessary to remove all traces of chemicals from the surface. After the parts are cleaned they must be protected from reoxidation. This is best done by storing in an inert gas chamber or in a vacuum chamber.

Molybdenum is welded by the gas tungsten arc welding process and the electron beam process. The gas metal arc process can be used but sufficient thickness of molybdenum is rarely available to justify this process. It has been welded by other arc processes but results are not too satisfactory. Welding with the gas shielding processes is accomplished in an inert gas chamber or dry box. This is a chamber that can be evacuated and purged with inert gas until all active gases are removed. A typical dry box welding chamber is shown in Figure 17-25. Welding is done in the pure inert atmosphere. The filler metal compositions should be the same as the base metal. The base metal in the heat-affected zone becomes embrittled by grain growth and recrystallization as a result of the welding temperatures. Recrystallization raises the transition temperature so that molybdenum welds tend to be brittle. Molybdenum is highly notch sensitive, craters and notch effects such as undercutting must be avoided. Molybdenum can also be welded with the resistance welding processes and by diffusion welding.

FIGURE 17-25 Welding in a dry box.

Tungsten is welded in the same manner as molybdenum and has the same problems, only more intensely so. It has greater susceptibility to cracking because the ductile-to-brittle transition temperatures are higher. The preparation of tungsten for welding is more difficult. The gas tungsten arc welding process is used with direct current electrode negative. Welding should be done slowly to avoid cracking. Preheating may assist in reducing cracking but must be done in the inert gas atmosphere.

Commercially pure tantalum is soft and ductile and does not seem to have a ductile–brittle transition. There are several alloys of tantalum commercially available. Even though the material is easier to weld, it should be well cleaned and for best results should be welded in the inert-gas chamber. The gas tungsten arc welding process is recommended. Some tantalum products are produced by powder metallurgy technology and this may result in porosity in the weld. The arc cast product does not have porosity. Filler wire is normally not used when welding tantalum and for best results direct current electrode negative is used. High frequency should be used for ini-

tiating the arc. Helium is recommended for welding tantalum to provide for maximum penetration since joints are designed to avoid using filler metal.

There are several different alloys of columbium (niobium) available. Some are ductile and others brittle since the transition temperature is near room temperature. The gas tungsten arc welding process is used for pure columbium and for the lower strength commercial alloys. In certain alloys the welding can be done outside of an inert gas chamber but special precautions should be taken to provide extremely good inert gas shielding coverage. In certain of the alloys preheating is recommended to provide for a crack-free weld. Electron beam welding is used and columbium can be resistance welded.

Reactive Metals

Beryllium has been welded with the gas tungsten arc welding process and with the gas metal arc welding process. It is also joined by brazing. Beryllium should not be welded without expert technical assistance. Beryllium is a toxic metal and extra special precautions should be provided for proper ventilation and handling.

Zirconium and zirconium-tin alloys are ductile metals and can be prepared by conventional processes. Cleaning is extremely important and chemical cleaning is preferred over mechanical cleaning. Both gas tungsten arc welding and gas metal arc welding are used for joining zirconium. The inert gas chamber should be employed to maintain an efficient gas shield. Argon or argon-helium mixtures are used. The zircalloys are alloys of zirconium which contain small amounts of tin, iron, and chromium. These alloys can be welded in the open in much the same manner as titanium. Electron beam and resistance welding have been used for joining zirconium.

The secret to the successful welding of titanium is *cleanliness*. Small amounts of contamination can render a titanium weld completely brittle. Contamination from grease, oils, paint, fingerprints, or dirt, and so on, can have the same effect. If the material is cleaned thoroughly before welding and well protected during welding there is little difficulty in the welding of titanium.

Gas tungsten arc and gas metal arc welding can be used for welding titanium. Special procedures must be employed which include the use of large gas nozzles and trailing shields to shield the face of the weld from air. Backing bars that provide inert gas to shield the back of the welds from air are used. Not only the molten weld metal, but the material heated above 1000 °F by the weld must be adequately shielded in order to prevent embrittlement.

When using GTAW a thoriated tungsten electrode should be used. The electrode size should be the smallest diameter that will carry the welding current. The electrode should be ground to a point. The electrode may extend 1½ times its diameter beyond the end of the nozzle. Welding is done with direct current, electrode negative (straight polarity).

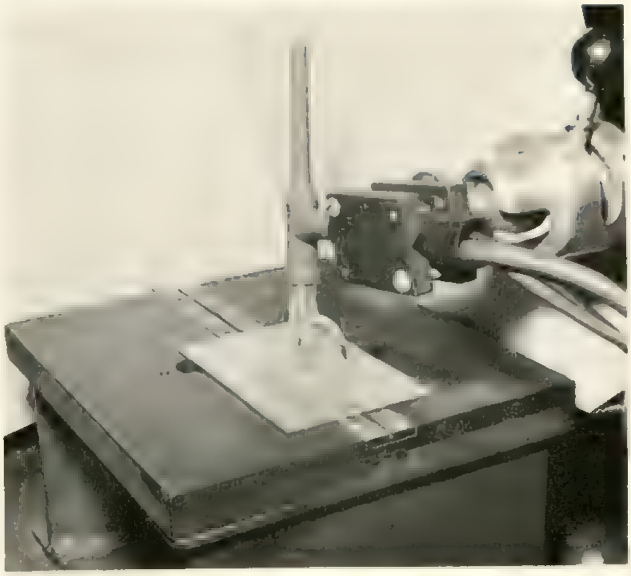
Selection of the filler metal will depend on the titanium alloys being joined. When welding pure titanium, pure titanium should be used. When welding a titanium alloy, the next lower strength alloy should be employed as a filler wire. Due to the dilution which will take place during welding the weld deposit will pick up the required strength. The same considerations are true when GMAW is used.

Argon is normally used with the gas-shielded process. For thicker metal use helium or a mixture of argon and helium. The purity of welding grade gases is normally satisfactory; however, tests can be made before welding. A simple test is to make a bead on a piece of clean titanium scrap and notice its color. The bead should be shiny. Any discoloration of the surface indicates a contamination.

Extra gas shielding provides protection for the heated solid metal next to the weld metal. This shielding is provided by special trailing gas nozzles (Figure 17-26) or by chill bars laid immediately next to the weld. Backup gas shielding should be provided to protect the underside of the weld joint. Protection of the back side of the joint can also be provided by placing chill bars in intimate contact with the backing strips. If the contact is close enough, backup shielding gas is not required. For critical applications use an inert-gas welding chamber. These can either be flexible, rigid, or vacuum purge chambers.

To guarantee that embrittlement of the weld will not occur, proper cleaning steps must be taken. Solvents containing chlorine should not be used. Recommended solvents would be trialcohol or acetone. Titanium can be ground with disks of aluminum oxide or silicon carbide.

FIGURE 17-26 Trailing shield on welding torch.



Material Thickness (or Fillet Size) ga	in.	mm	Type of Weld Fillet or Groove	Tungsten Electrode Diameter in.	mm	Filler Rod Diameter in.	mm	Nozzle Size Inside Dia. in.	Shielding Gas Flow cfh	Welding Current Amps DCEN	No. of Passes	Travel Speed (per pass) ipm
24	0.024	0.6	Sq. groove & fillet	1/16	1.6	None		3/8	18	20-35	1	6
16	0.063	1.6	Sq. groove & fillet	1/16	1.6	None		5/8	18	85-140	1	6
3/32	0.093	1.6	Sq. groove & fillet	3/32	2.4	1/16	1.6	5/8	25	170-215	1	8
1/8	0.125	3.2	Sq. groove & fillet	3/32	2/4	1/16	1.6	5/8	25	190-235	1	8
3/16	0.188	4.8	Sq. groove & fillet	3/32	2.4	1/8	3.2	5/8	25	220-280	2	8
1/4	0.25	6.4	Vee groove & fillet	1/8	3.2	1/8	3.2	5/8	30	275-320	2	8
3/8	0.375	9.5	Vee groove & fillet	1/8	3.2	1/8	3.2	3/4	35	300-350	2	6
1/2	0.50	12.7	Vee groove & fillet	1/8	3.2	5/32	3.9	3/4	40	325-425	3	6

1 - Tungsten used, 1st choice 2% thoriated EWTh2—2nd choice 1% thoriated EWTh1.

2 - Use filler metal one or two grades lower in strength than the base metal.

3 - Adequate gas shielding is a must not only for the arc but also heated metal. Backing gas is recommended at all times. A trailing gas shield is also recommended. Argon is preferred for higher heat input on thicker material use Argon-Helium mixture.

4 - Without backup or chill bar, decrease current 20%.

FIGURE 17-27 Welding procedure schedules for GTAW of titanium.

Wet grinding is preferred; however, if wet grinding cannot be used, the grinding should be done slowly to avoid overheating the surface of the titanium.

Figure 17-27 gives procedure schedules for welding titanium. Joint types that are satisfactory for stainless steel should be used.

17-6 THE OTHER NONFERROUS METALS

This section covers the welding of the low-melting-point metals, lead and zinc, and the precious metals, silver, gold, and platinum. Lead has one of the lowest melting temperatures. It melts at 621 °F (328 °C) and boils at 3092 °F (1700 °C). It is very soft and very ductile. When freshly cut its surface has a bright silvery luster which almost immediately oxidizes to a dull gray. It is available in sheet form and is used as a liner for tanks because of its corrosion resistance, particularly to sulfuric acid. It is also available in pipe.

Lead is normally joined by the oxyacetylene or oxyfuel gas torch and for this reason has erroneously been called lead burning. Lead can also be welded with the gas tungsten arc welding process. Since lead is usually in thin sheets, the square butt and lap joints are the most commonly used. The surface of the lead at the welding area should be cleaned. Filler metal can be obtained by shearing strips of the base metal.

Sufficient heat is obtained to melt the surface of the base metal and the filler rod when used. When using gas tungsten arc a long arc is recommended to reduce the actual heat in the joint. There are a few difficulties that can be encountered when welding lead. Its popularity and use is declining and for this reason the joining of lead is of minor importance. Proper ventilation is required.

Zinc is much similar to lead except that it is not as heavy. Zinc is widely used as a coating on steel which is called galvanized steel. Zinc also has a tough oxide coating which must be removed prior to welding. The major use of zinc where welding is involved is as high-zinc die castings. Die castings of this type are commonly used for automotive grills and for decorative trim. For decorative trim and grills, the zinc may be chromium plated. It is important to distinguish zinc die castings from aluminum and magnesium alloy castings. Zinc has a weight in the same order as steel. In addition, the zinc has a light gray appearance which is rather easy to identify.

The oxyacetylene or oxyfuel gas torch method is used to weld zinc alloys, particularly the die castings. The technique is essentially the same as for lead. The filler metal for matching zinc die castings is difficult to obtain and for this reason it may be necessary to manufacture it. One way is to melt down the bodies of carburetors and pour into a groove formed when an angle iron is positioned with the point down. These alloys contain approximately 10% aluminum, 1 to 2½% copper, a trace of magnesium, with the remainder zinc.

For welding die castings the joint must be prepared with an extra wide root angle approaching 90°. The part should be positioned and braced in position. If the part is chrome plated, the plating should be removed adjacent to the welding area. The surfaces to be welded should be cleaned by wire brushing, sanding, filing, and so on. In addition, the filler metal should be cleaned by sanding. A small size torch should be used and only sufficient heat to melt the surface and the filler rod. The filler rod is handled in the same manner as with lead welding.

The gas tungsten arc welding process can also be used for welding zinc die-casting alloys. When using the gas tungsten torch a small tungsten and low current

should be employed. Sufficient heat should be maintained to melt the surface of the work being welded. The filler rod is moved in and out of the molten puddle, normally on the leading edge. If the part is unusually shaped, it may be necessary to back it up to maintain the shape of the part. Proper ventilation is required.

Welding the Precious Metals

Silver is welded in much the same manner as copper since it has a high conductivity and a low affinity for oxygen and nitrogen. Filler metal normally used for brazing can be used. Silver is used for jewelry and tableware, but also for industrial applications where tanks are lined with sheet silver for the chemical industry.

The oxyacetylene or oxyfuel gas torch has been widely used for welding silver. Silver is also clad to other metals for chemical vessels. The gas tungsten arc welding process can also be used for welding silver and in this case direct current electrode negative is employed. The torch or tungsten must be sufficiently small to match the welding job. Procedure data for welding pure copper can be used to establish starting points for a silver welding procedure. Silver is also brazed and soldered.

Gold is one of the most expensive metals and, therefore, parts to be welded are unusually thin or small intricate shape. Gold can be soldered or brazed and it may be cold or pressure welded. It is normally welded with the oxyfuel gas process using the small torch.

Platinum is used in the chemical industry and in the glass industry for making filaments for fiberglass. Welding is often required and is normally accomplished by the oxyacetylene or oxyfuel gas and the gas tungsten arc welding process. The other precious metals of the platinum group can be welded in the same manner. All the precious metals can be resistance welded, in spite of their high conductivity. The plasma arc welding process can also be used.

QUESTIONS

17-1. Explain the aluminum designation system of alloys and tempers.

17-2. What properties of aluminum make it different from welding steel? Explain.

17-3. What are the two most popular processes for welding aluminum? Where is each used?

17-4. Of all the factors involved in welding aluminum, which one is the most important?

17-5. What are the properties of copper and its alloys that make welding difficult?

17-6. What is the effect of zinc in copper alloys on welding?

17-7. What problem does magnesium oxide present when welding magnesium?

17-8. Welding nickel and high-nickel alloys is similar to welding what other metals?

17-9. Why should the bevel or groove angles be increased for nickel alloys?

17-10. What welding process is most widely used for welding nickel alloys?

17-11. What are the reactive metals? Why are they difficult to weld?

17-12. What precautions should be taken when welding beryllium or its alloys?

17-13. What welding processes are used to join titanium *in the open*?

17-14. What is the most important factor to consider when welding titanium?

17-15. What precautions must be taken when welding lead?

17-16. What filler metal is used for lead? Where is it obtained?

17-17. Can zinc die castings be welded? How?

17-18. What precautions must be taken when welding zinc?

17-19. Silver is welded in much the same way as what other metal?

17-20. What processes are commonly used to join gold?

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18

Welding Special and Dissimilar Metals

OUTLINE

18-1 CAST IRON AND OTHER IRONS

The term *cast iron* is a rather broad description of many types of irons which are castings but which may have different properties and serve different purposes. In general, a cast iron is an alloy of iron, carbon, and silicon in which more carbon is present than can be retained in solid solution in austenite at the Eutectic temperature. The amount of carbon is usually more than 1.7% and less than 4.5%. There are many types of cast iron. The most widely used type of cast iron is known as gray iron. Its tonnage production exceeds that of any other cast metal.

Gray iron has a variety of compositions but it is usually such that the matrix structure is primarily pearlite with many graphite flakes dispersed throughout. It is these graphite flakes that provide the characteristic "gray" appearance of the fracture. The graphite flakes promote machinability which is one of the primary ad-

vantages of gray cast iron. Another advantage is the ability to cast material into complex shapes with relatively thin walls. Gray cast iron is the least expensive metal for making many parts. Gray cast iron also has good resistance to wear and seems to have a damping effect for vibration.

Gray cast iron is used in the automotive industry for: engine blocks and heads, automatic transmission housings, differential housings, water pump housings, brake drums, and engine pistons. There are exceptions to this but the exceptions are usually aluminum, which is readily identifiable from cast iron.

There are also alloy cast irons which contain small amounts of chromium, nickel, molybdenum, copper, or other elements added to provide specific properties. These usually provide higher-strength cast irons. One of the major uses for the higher-strength irons is casting automotive crankshafts. These are sometimes called semisteel or proprietory names.

Another alloy iron is the austenitic cast iron, which is modified by additions of nickel and other elements to reduce the transformation temperature so that the structure is austenitic at room or normal temperatures. Austenitic cast irons have a high dregree of corrosion resistance.

Another type of cast iron is known as white cast iron, in which almost all the carbon is in the combined form. This provides a cast iron with higher hardness which is used for abrasion resistance.

One class of cast iron is called malleable iron. This is made by giving white cast iron a special annealing heat treatment to change the structure of the carbon in the iron. By so doing, the structure is changed to pearlitic or ferritic which increases its ductility.

There are two other classes of cast iron which are more ductile than gray cast iron. These are known as nodular iron and ductile cast iron. These are made by the addition of magnesium or aluminum which will either tie up the carbon in a combined state or will give the free carbon a spherical or nodular shape rather than the normal flake shape in gray cast iron. This structure provides a greater degree of ductility or malleability of the casting.

Cast irons are used in many industries and they are popular because of their ease of casting, the ease of machining, and the relative low cost compared to other metals. They are widely used in agricultural equipment, for bases, brackets, covers, and so on, on machine tools, and for pipe fittings and for cast iron pipe. Cast iron is rarely used in structural work except for compression members.

Cast irons, particularly gray cast irons, are covered by ASTM specification A48, which establishes seven classes based on the tensile strength of the material. These range from 20,000 psi (14.5 kg/mm^2) tensile and 150 Brinell hardness number to 40,000 psi (28.5 kg/mm^2) and 250 Brinell hardness number. The cast irons above 40,000 psi (28.5 kg/mm^2) tensile strength are considered high-strength irons and are more expensive and more difficult to machine. Cast iron is twice as strong in compression than in tension. Other ASTM specifications are used to describe other classes of cast iron, but these are primarily with respect to the end use of the material.

Welding the Cast Irons

The gray cast iron has a very low ductility. Possibly a maximum of 2% ductility will be obtained in the extreme low carbon range. The low ductility is due to the presence of the graphite flakes, which act as discontinuities. In most welding processes the heating and cooling cycle creates expansion and contraction, which sets up tensile stresses during the contraction period. For this reason, gray cast iron is difficult to weld without special precautions. The ductile cast irons, such as malleable iron, ductile iron, and nodular iron, can be welded successfully. For best results, these types of cast irons should be welded in the annealed condition.

Welding is used to salvage new iron castings, to repair castings that have failed in service and to join castings to each other or to steel parts in manufacturing operations. Figure 18-1 shows the welding processes that can be used for welding cast, malleable, and nodular irons. The selection of the welding process and the welding filler metals depends on the type of weld properties desired and the service life that is expected. The filler metal will have an effect on the color match of the weld compared to the base material. The color match can be a determining factor, specifically in the salvage or repair of castings, where a difference of color would not be acceptable.

No matter which welding process is selected, certain preparatory steps should be made. It is important to determine the exact type of cast iron to be welded. If exact information is not known it is best to assume that it is gray cast iron with little or no ductility. This would err on the side of safety so that a successful repair weld would be obtained.

In general it is not recommended to weld repair gray iron castings that are subjected to heating and cooling in normal service. At least it should not be used when heating and cooling vary over a range of temperatures exceeding 400°F (204°C). The reason is that unless cast iron is used as the filler material, the weld metal and base metal may have different coefficients of expansion and contraction. This will contribute to internal stresses which cannot be withstood by gray cast iron. Repair of these types of castings can be made, but the reliability and service life of such repairs cannot be predicted with accuracy.

Preparation for Welding

In preparing the casting for welding it is necessary to remove all surface materials to completely clean the

Welding Process & Filler Metal Type	Filler Metal Spec[1]	Filler Metal Type[1]	Color Match	Machineable Deposit
SMAW (Stick)				
Cast iron	E-CI	Cast iron	Good	Yes
Copper-tin[2]	ECuSn A & C	Copper—5 or 8% tin	No	Yes
Copper-aluminum[2]	ECuAl-A2	Copper-10% aluminum	No	Yes
Mild steel	E-St	Mild steel	Fair	No
Nickel	ENi-CI	High nickel alloy	No	Yes
Nickel-iron	ENiFe-CI	50% Nickel plus iron	No	Yes
Nickel-copper	ENiCu-A & B	55 or 65% Ni + 40 or 30% W	No	Yes
Oxy Fuel Gas				
Cast iron	RCI & A & B	Cast iron—with minor alloys	Good	Yes
Copper zinc[2]	RCuZn B & C	58% Copper—zinc	No	Yes
Brazing[3]				
Copper Zinc	RBCuZn A & D	Copper-zinc & copper-Zinc-nickel	No	Yes
GMAW (MIG)				
Mild steel	E60S-3	Mild steel	Fair	No
Copper base[2]	ECuZn-C	Silicon bronze	No	Yes
Nickel-copper	ENiCu-B	High nickel	No	Yes
FCAW				
Mild steel	E70T-7	Mild steel	Fair	No
Nickel type	No spec	50% Nickel plus iron	No	Yes

Note: (1) See AWS Specification for Welding Rods and Covered Electrode for Welding Cast Iron.[1]
(2) Would be considered a brass weld.
(3) Heat source any for brazing also carbon arc, twin carbon arc, gas tungsten arc or plasma arc.

FIGURE 18-1 Welding processes and filler metals for cast iron.

casting in the area of the weld. This means removing paint, grease, oil, and other foreign material from the weld zone. It is desirable to heat the weld area for a short time to remove entrapped gas from the weld zone of the base metal. Additionally, the skin or high-silicon surface should be removed adjacent to the weld area on both the face and root side.

Where grooves are involved a V groove from a 60–90° included angle should be used. Complete penetration welds should always be used since a crack or defect not removed completely may quickly reappear under service conditions.

Preheating is desirable for welding. It can be reduced when using extremely ductile filler metal. Preheating will reduce the thermal gradiant between the weld and the remainder of the cast iron. Preheat temperatures should be related to the welding process, the filler metal type, the mass, and the complexity of the casting.

Preheating can be done by any of the normal methods. Torch heating is normally used for relatively small castings weighing 30 lb (13.6 kg) or less. Larger parts may be furnace preheated and in some cases temporary furnaces are built around the part rather than taking the part to a furnace. Preheating should be general since it helps to improve the ductility of the material and will spread shrinkage stresses over a large area to avoid critical stresses at any one point. It tends to help soften the area adjacent to the weld; it assists in degassing the casting and this in turn reduces the possibility of porosity of the deposited weld metal; and it also increases welding speed.

Slow cooling or post heating improves the machinability of the heat-affected zone in the cast iron adjacent to the weld. The post cooling should be as slow as possible. Often this is done by covering the casting with insulating materials to keep the air or breezes from it.

Arc Welding

The shielded metal arc welding process can be utilized. There are four types of filler metals that may be used: cast iron covered electrodes, covered copper-base alloy electrodes, covered nickel-base alloy electrodes, and mild steel covered electrodes. There are reasons for using each of the different specific types of electrodes: the machinability of the deposit, the color match of the deposit, the strength of the deposit, and the ductility of the final weld.

When arc welding with the cast iron electrodes (ECI), preheat to between 250 and 800°F (121 and 425°C), depending on the size and complexity of the casting and the need to machine the deposit and adjacent areas. The higher the degree of heating, the easier

it will be to machine the weld deposit. In general, it is best to use small electrodes and a relatively low current setting. A medium arc length should be used, and if at all possible welding should be done in the flat position. Wandering or skip welding procedures should be used, and peening will help reduce stresses and will minimize distortion. Slow cooling after welding is recommended. These electrodes provide an excellent color match on gray iron. The strength of the weld will equal the strength of the base metal.

There are two types of copper-base electrodes, the copper–tin alloy (ECuSn-A and C) and the copper–aluminum (ECuA1-A2) types. The copper–zinc alloys cannot be used for arc welding electrodes because of the low boiling temperature of zinc. Zinc will volatilize in the arc and will cause weld metal porosity. The copper tin electrodes will produce a bronze weld having good ductility. The ECuSn-A has less amount of tin. It is more of a general-purpose electrode. The ECuSn-C provides a stronger deposit with higher hardness. The copper–aluminum alloy electrode (ECuA1-A2) provides much stronger welds and is used on the higher-strength alloy cast irons.

When the copper-base electrodes are used, a preheat of 250 to 400 °F (121 to 204 °C) is recommended and small electrodes and low current should be used. The welding technique should be to direct the arc against the deposited metal or puddle to avoid penetration and mixing the base metal with the weld metal. Slow cooling is recommended after welding.The copper-base electrodes do not provide a color match.

There are three types of nickel electrodes used for welding cast iron. The ENiFe-CI contains approximately 50% nickel with iron, the ENiCI contains about 85% nickel, and the ENiCu type contains nickel and copper. The ENiFeCI electrode is less expensive and provides results approximately equal to the high-nickel electrode. These electrodes can be used without preheat; however, heating to 100 °F (38 °C) is recommended. These electrodes can be used in all positions; however, the flat position is recommended. The welding slag should be removed between passes. The nickel and nickel iron deposits are extremely ductile and will not become brittle with the carbon pickup. The hardness of the heat-affected zone can be minimized by reducing penetration into the cast iron base metal. The technique mentioned above, that is, playing the arc on the puddle rather than on the base metal, will help minimize dilution. Slow cooling and if necessary postheating will improve machinability of the heat-affected zone. The nickel-base electrodes do not provide a close color match.

The copper–nickel type comes in two grades; the ENiCu-A with 55% nickel and 40% copper and the ENiCu-B with 65% nickel and 30% copper. Either of these electrodes can be used in the same manner as the nickel or nickel–iron electrode with about the same technique and results. The deposits of these electrodes do not provide a color match.

Mild steel electrodes (E St) are not recommended for welding cast iron if the deposit is to be machined. The mild steel deposit will pick up sufficient carbon to make a high-carbon deposit which is impossible to machine. Additionally, the mild steel deposit will have a reduced level of ductility as a result of increased carbon content. This type of electrode should be used only for small repairs. Minimum preheat is possible for small repair jobs. Small electrodes at low current are recommended to minimize dilution, and to avoid the concentration of shrinkage stresses. Short welds using a wandering sequence should be used and the weld should be peened as quickly as possible after welding. The mild steel electrode deposit provides a fair color match.

Oxyfuel Gas Welding

The oxyfuel gas process is often used for welding cast iron. The flame should be neutral to slightly reducing. Flux should be used. Two types of filler metals are available: the cast iron rods (RCI and A and B) and the copper zinc rods (RCuZn-B and C).

Welds made with the proper cast iron electrode will be as strong as the base metal. The RCI classification is used for ordinary gray cast iron. The RCI-A has small amounts of alloy and is used for the high strength alloy cast irons and the RCI-B is used for welding malleable and nodular cast iron. Good color match is provided by all these welding rods. The optimum welding procedure should be used with regard to joint preparation, preheat, and post heat.

The copper–zinc rods produce bronze welds. There are two classifications: RCuZn-B, which is a manganese bronze, and RCuZn-C, which is a low-fuming bronze. The bronze deposited has relatively high ductility but will not provide a color match.

Brazing and Braze Welding

Brazing is used for joining cast iron to cast iron and steels. In these cases, the joint design must be selected for brazing so that capillary attraction causes the filler metal to flow between closely fitting parts. The torch method is normally used; however, any of the other heating methods can be used. In addition, the carbon arc, the twin carbon arc, the gas tungsten arc, and the plasma arc can all be used as sources of heat. Two brazing filler metal alloys are normally used, both copper–zinc alloys; see Figure 18-1 for specification for the brazing alloys.

Braze welding can also be used to join cast iron. In braze welding the filler metal is not drawn into the joint by capillary attraction. This is sometimes called bronze welding. The filler material having a liquidous above 850 °F (454 °C) should be used. Braze welding will not provide a color match.

Braze welding can also be accomplished by the shielded metal arc and the gas metal arc welding processes. High-temperature preheating is not usually required for braze welding unless the part is extremely heavy or complex in geometry. The bronze weld metal deposit has extremely high ductility, which compensates for the lack of ductility of the cast iron. The reason for not requiring high-temperature preheat is the desire to avoid intermix of base metal with the filler metal. The heat of the arc is sufficient to bring the surface of the cast iron up to a temperature at which the copper-base filler metal alloy will make a bond to the cast iron. Since there is little or no intermixing of the materials the zone adjacent to the weld in the base metal is not appreciably hardened. The weld and adjacent area are machinable after the weld is completed. In general, a 200 °F (93 °C) preheat is sufficient for most applications. The cooling rate is not extremely critical and a stress relief heat treatment is not usually required. This type of welding is commonly used for repair welding of automotive parts, agricultural implement parts, and even automotive engine blocks and heads. It can be used only when the absence of color match is not objectionable.

Gas Metal Arc Welding

The gas metal arc welding process can be used for making welds between malleable iron and carbon steels. Several types of electrode wires can be used,[2] including:

- Mild steel (E70S-3) using 75% argon + 25% CO_2 for shielding.
- Nickel–copper (ENiCu-B) using 100% argon for shielding.
- Silicon bronze (ECuZn-C) using 50% argon + 50% helium for shielding.

In all cases small-diameter electrode wire should be used at low current. With the mild steel electrode wire the argon–Co_2 shielding-gas mixture is used to minimize penetration. In the case of the nickel-base filler metal and the copper-base filler metal, the filler metal deposited is extremely ductile. The mild steel provides a fair color match. A higher preheat is usually required to reduce residual stresses and cracking tendencies.

Flux-Cored Arc Welding

This process has recently been used for welding cast irons. The more successful application has been using a nickel-base flux-cored wire which produces a weld metal deposit very similar to the 50% nickel deposit provided by the ENiFe-CI covered electrode. This electrode wire is normally operated with CO_2 shielding gas, but when lower mechanical properties are not objectionable it can be operated without external shielding gas. The minimum preheat temperatures can be used. The techinque should minimize penetration into the cast iron base metal. Postheating is normally not required. A color match is not obtained.

Flux-cored self-shielding elecrtrode wires (E60T-7), operating with electrode negative (straight polarity), have also been used for certain cast iron to mild steel applications. In this case, a minimum penetration type weld is obtained and by the proper technique penetration should be kept to a minimum. It is not recommended for deposits that must be machined.

Figure 18-1 provides a summary of welding processes for joining cast iron. For manufacturing operations it is highly recommended that a welding procedure be developed utilizing the process selected and that service-type tests be made prior to using the process on a particular product. In general, those cast irons having maximum ductility are those that can be most successfully welded. Thus malleable iron, nodular iron, and ductile iron can be welded for many applications. The most successful welds would be those that provide an extremely ductile weld deposit.

Other welding processes can also be used for cast iron. Thermit welding has been used for repairing certain types of cast iron machine tool parts. The procedure is identical to that used for welding steel except that a special thermit mixture is required. Flash welding can also be used for welding cast iron.

18-2 TOOL STEELS

Steels used for making tools, punches, and dies are perhaps the hardest, the strongest, and toughest steels used in the industry. It is obvious that tools used for working steels and other metals must be stronger and harder than the steels or material they cut or form. The metallurgical characteristics of various compositions of tool steels are extremely complex and beyond the scope of this book. Tools and dies wear and are damaged but by means of welding they can be repaired and returned to service. In addition, certain kinds of tools and dies can be fabricated by welding. The repairing of damaged tools and dies and the fabrication by welding of dies will save money.

There are hundreds of different makes and types of tool steels available and each may have a specific composition and end use. The Society of Automotive Engineers, in cooperation with the American Iron and Steel Institute, has established a classification system which relates to the use of the material and its composition or type of heat treatment. This classification system divides the tool and die steels into separate categories (Figure 18-2). In general, tool steels are basically medium- to high-carbon steels with specific elements included in different amounts to provide special characteristics. The

AISI-SAE Types	Classification of Tools Steels	COMPOSITION %					
		C	Cr	V	W	Mo	Other
W1	Water hardening	0.60	—	—	—	—	—
W2		0.60	—	0.25	—	—	—
S1		0.50	1.50	—	2.50	—	—
S5	Shock resisting	0.55	—	—	—	0.40	0.80 Mn 2.00 Si
S7		0.50	3.25	—	—	1.40	—
O1	Oil hardening	0.90	0.50	—	0.50	—	—
O6		1.45	—	—	—	0.25	1.00 Si
A2	Cold work	1.00	5.00	—	—	1.00	—
A4	Medium alloy air hardening	1.00	1.00	—	—	1.00	2.00 Mn
D2	Cold work High carbon High chromium	1.50	12.00	—	—	1.00	—
M1	Cold work	0.80	4.00	1.00	1.50	8.00	—
M2	Molybdenum	0.85	4.00	2.00	6.00	5.00	—
M10		0.90	4.00	2.00	—	8.00	—
H11	Hot work	0.35	5.00	0.40	—	1.50	—
H12	Chromium	0.35	5.00	0.40	1.50	1.50	—
H13		0.35	5.00	1.00	—	1.50	—
P20	Die casting mold	0.35	1.25	—	—	0.40	—

FIGURE 18-2 Abridged chart of tool steel types.

carbon in the tool steel is provided to help harden the steel to greater hardness for cutting and wear resistance. Other elements are added to provide greater toughness or strength.

The addition of elements produces different effects on the resultant composition as follows: Chromium produces deeper hardness penetration in heat treatment and contributes wear resistance and toughness. Cobalt is used in high-speed steels and increases the red hardness so that they can be used at higher operating temperatures. Manganese in small amounts is used to aid in making steel sound and further additions help steel to harden deeper and more quickly in heat treatment. It also helps to lower the quenching temperature necessary to harden steels. Larger amounts of manganese in the range 1.20 to 1.60% allow steels to be oil quenched rather than water quenched. Molybdenum increases the hardness penetration in heat treatment and reduces quenching temperatures. It also helps increase red hardness and wear resistance. Nickel adds toughness and wear resistance to steel and is used in conjunction with hardening elements. Tungsten added to the steel increases its wear resistance and provides red hardness characteristics. Approximately 1.5% increases wear resistance and about 4% in combination with high carbon will greatly increase wear resistance. Tungsten in large quantities with chromium provides for red hardness. Vanadium in small quantities increases the toughening effect and reduces grain size. Vanadium in amounts over 1% provides extreme wear resistance especially to high-speed steels. Smaller amounts of vanadium in conjunction with chromium, and tungsten, aid in increasing red hardness properties.

The tool or die steels are designed for special purposes that are dependent on composition. Certain tool steels are made for producing die blocks; some are made for producing molds, others are made for hot working, and still others for high-speed cutting applications. The other way for classifying tool steels is according to the type of quench required to harden the steel. The most severe quench after heating is the water quench, (water-hardening steels). A less severe quench is the oil quench obtained by cooling the tool steel in oil baths (oil-hardening steels). The least drastic quench is cooling in air (air-hardening steels).

Tool steels and dies can also be classified according to the work that is to be done by the tool. This is based on class numbers. Class I steels are used to make tools that work by a shearing or cutting action, such as cutoff dies, shearing dies, blanking dies, trimming dies, and so on. Class II steels are used to make tools that produce the desired shape of the part by causing the material being worked, either hot or cold, to *flow* under tension. This includes drawing dies, forming dies, reducing dies, forging dies, and so on. This class also includes plastic molds and die cast molding dies. The Class III steels are used to make tools that act on the material being worked by partially or wholly reforming it without changing the actual dimensions. This includes bending dies, folding dies, twisting dies, and so on. Class IV steels are used to make dies that work under heavy pressure and that produce a flow of metal or other material compressing it into the desired form. This includes crimping dies, embossing dies, heading dies, extrusion dies, staking dies, and so on. It is important to understand and have suffi-

cient information concerning the composition of the tool or die, the type of heat treatment that it has received, and the type of work that it performs.

As far as welding is concerned, there are four basic types of die steels that are weld repairable: water-hardening dies, oil-hardening dies, air-hardening dies, and hot work tools. High-speed tools can also be repaired. In tool and die welding it is not always necessary for the electrode used to provide a deposited weld metal that exactly matches the analysis of the tool steel being welded. It is necessary, however, that the weld metal deposited match the heat treatment of the tool or die steel as closely as possible. Thus selection of the proper electrode is based on matching the heat treatment of the tool or die steel.

There are no specifications covering the composition of tool and die welding electrodes. However, all manufacturers of these types of electrodes provide information concerning each of their electrodes showing the type of tool or die steels for which it is designed. They also provide the properties of the weld metal that is deposited. Welding electrodes are not available to match the composition of each and every tool steel composition or to match the specific heat treatment of each tool or die steel. However, tool and die electrodes are available that match the different categories of tool and die steels. Assistance can be obtained from the catalogs of electrodes for this type of welding or by consulting with representatives of the companies that manufacture these electrodes. If the identification of the electrodes is lost it is possible to use the spark test in matching the electrode to the tool steel. A comparison is made of the sparks from the tool or die steel to be welded and compared with the spark pattern of the welding electrode. The matching spark patterns will be the guide or basis for selection of the electrode.

Successful tool and die welding depends on the selection or development of a welding procedure and welding sequence. It is beyond the scope of this chapter to outline specific welding procedures to be used for each classification of tool steel using each type of tool and die welding electrodes. Normally, the manufacturer of electrodes will provide specific procedure sheets pertaining to the different electrodes they offer. These should be carefully followed.

In general, weld deposits of tool and die electrodes are sufficiently hard in the as-welded condition. If the welded tools or dies lend themselves to grinding, treatment other than tempering is not required. However, if machining is required the weld deposits should be annealed and heat treated after machining. The hardness of the weld deposit will vary in accordance with the following:

- ☐ Preheat temperature if used
- ☐ Welding technique and sequence
- ☐ Mixture or dilution of the weld metal with base metal
- ☐ Rate of cooling, which depends on the mass of the tool being welded
- ☐ Tempering temperature of the welded tool or die after welding

Uniform hardness of the as-welded deposit is obtained if the temperature of the tool or die is maintained constant during the welding operation. The temperature of the tool or die being welded should never exceed the maximum of the *draw range* temperature for the particular class of tool steel being welded. The manufacturer's recommendation should be followed with respect to those temperatures.

The welding procedure for repair welding of tools and dies should consist of at least the following factors:

- ☐ Identification of the tool steel being welded
- ☐ Selection of the electrode to match the same class of material or heat treatment
- ☐ Establishing the correct joint detail for the repair and preparing the joint
- ☐ Preheating the workpiece
- ☐ Making the weld deposit in accordance with manufacturer's recommendations
- ☐ Postheating to temper the deposit or the repaired part

One of the major problems is proper preparation of the part for repair welding. When making large repairs to worn cutting edges or surfaces the damaged area should be ground sufficiently under size to allow a uniform depth of finished deposit of at least ⅛ in. (3.2 mm). In some cases very small weld deposits are made using the gas tungsten arc welding process to build up a worn or damaged edge or corner. It is important to provide a uniformly thick weld deposit which will be refinished to the original dimensions. This ensures a more uniform hardness throughout the deposit. For inlay deposit or other overlay work a thickness of $\frac{3}{16}$ in. (4.8 mm) is required.

When preheating the part to be repaired, observe the "draw temperature range" of the base metal. The preheat temperature should slightly exceed the minimum of the draw range and the interpass temperature should never exceed the maximum of the draw range of the particular tool steel. Exceeding the maximum draw range will reduce the hardness of the tool by softening it. Figure 18-3 provides recommended preheat temperatures to be employed on some of the popular types of tool steels.

Most of the tool and die welding electrodes are used with dc electrode positive or with alternating current. The recommended currents for each different size should be

AISI-SAE Type	Preheat Temperature °F	Interpass Temperature °F	Draw or Tempering Temperature °F
W1	250/450	250/450	300/650
W2	250/450	250/450	300/650
S1	300/500	300/500	300/500
S5	300/500	300/500	500 Min.
S7	300/500	300/500	425/400
O1	300/400	300/400	300/450
O6	300/400	300/400	300/450
A2	300/500	300/500	350/400
A4	300/500	300/500	350/400
D2	700/900	700/900	925/900
M1	950/1100	950/1100	1000/1050
M2	950/1100	950/1100	1000/1050
M10	950/1100	950/1100	950/1050
H11	900/1200	900/1200	1000/1150
H12	900/1200	900/1200	1000/1150
H13	900/1200	900/1200	1000/1150
P20	400/800	400/800	1000

FIGURE 18-3 Preheat and interpass temperatures when welding tool steels.

provided with the electrode manufacturer's technical data. For making tool and die welds a slow travel is recommended in order to maintain an even deposit and to assure uniform weld penetration. The work should be positioned for flat-position welding except that it is recommended that welding be done with the work positioned for slightly uphill travel, on the order of 5 to 15°. This causes the deposit to build up evenly and helps keep the slag free of the weld puddle. Uniform motion without weaving is recommended. When welding on tool cutting edges, position the work so that the deposit will flow or roll over the cutting edge.

Peening should be done immediately on all weld deposits. Peening, however, should be controlled. Peening should be used to provide sufficient mechanical work to help improve the properties of the deposit and help refine the metallurgical structure. It will also assist in relieving shrinkage stresses and possibly assist in correcting distortion. Peening can be done manually or small pneumatic power hammers can be used. The welding technique should avoid craters. In all cases, craters should be filled by reversing the direction of travel and pausing slightly. This will ensure a more uniform deposit.

When welding deeply damaged cutting edges that require multiple passes it is necessary to start at the bottom and gradually fill up damaged areas. The current for the first or second beads can be higher than used on the final bead. It is important to peen the weld metal while hot to help eliminate shrinkage, warpage, and possibly cracks. The random or wandering welding technique should be used when welding circular parts, such as on the inner edge of a die. Warpage or distortion can be reduced by preheating, which expands the part, and peening during the contraction period will reduce stresses. On parts such as a long shear blade where welding is done all on one side it is recommended that the parts be reverse formed. This will help keep the part straight during welding. It is recommended to weld only short lengths of 2 to 3 in. and then to peen to reduce stresses and warpage.

After the repair welds are completed the part may be allowed to cool to room temperature. It is then tempered by reheating to the recommended temperature, as specified by the type of tool steel being welded or by the welding electrode manufacturer's technical data. The draw temperature would always be used. For small or light-duty work parts, the draw temperature should be on the minimum side of the draw range. On larger or heavy-duty parts, the draw temperature should be on the maximum.

Composite dies manufactured by welding are becoming more popular. Tool steel is used for cutting or working surfaces and medium-carbon steel is used for the remainder of the part. This type of construction greatly reduces the cost of the composite die. The electrode is selected based on the type of tool steel employed. The weld preparation, preheat, and welding sequence would be the same as mentioned previously.

Experience with tool and die welding is very helpful and will avoid the possibility of failures. The procedure development, including identification of material, selection of electrodes, and welding techniques should follow the tool steel manufacturer's data and the welding electrode manufacturer's information.

18-3 REINFORCING BARS

Concrete reinforcing bars, or as they are more technically known, *deformed steel reinforcing bars*, are used in reinforced concrete construction. This includes buildings, bridges, highways, locks, dams, docks, piers, and so on. The principal applications of reinforcing bars include reinforcement of columns, girders, beams, slabs, pavements, as well as precast and prestressed concrete structures. Concrete is strong in compression and shear but is weak in tension. By using deformed steel reinforcing bars embedded in the concrete, tensile stresses can be accommodated; thus reinforced concrete provides compression strength of concrete and tensile strength of steel. The concrete and steel must work together. This is accomplished by a bond between the bar and the concrete, which is achieved by means of deformations which are rolled into the bars. These deformations keep the bars from slipping through the concrete.

Concrete reinforcing bars come in different sizes. There are 11 standard sizes, known as *reinforcing bar* No. 3 through No. 11 and No. 14 and No. 18. The numbers assigned to bars are based on the number of ⅛ in. included in the nominal diameter. The nominal diameter of a deformed reinforcement bar is equivalent to the diameter of a plain steel bar having the same weight per foot as the deformed bar. Lengths up to 60 ft are available.

There are three ASTM specifications for reinforcing bars: A615, plain billet steel bars; A616, rail steel reinforcing bars; and A617, axle steel reinforcement bars. Information concerning these different specifications is shown in Figure 18-4.

All of the reinforcing bars produced in the United States are identified by markings rolled into the bar. These markings will show the code for the manufacturer of the steel bar. The different code letters have been identified by the Concrete Reinforcing Steel Institute.[3] This is then followed by the letter identifying the specific steel mill where the bar was produced, based on standard designations. The next symbol indicates the bar size by the bar number. The next symbol indicates the type of steel as follows: N indicates new billet steel, A indicates axle steel, and the third symbol which is a cross section of a railroad rail indicates that the bar was rerolled from used railroad rails.

The next identification symbol is a number indicating the grade of steel. If there is no number, it normally means that it is the minimum grade within the specification. Grades are also identified by a single or double continuous longitudinal line through at least five spaces offset from the center of the bar. A single line indicates the middle-strength grade and a double line indicates the highest-strength grade. It is important to determine the type of steel and the grade since this will be valuable information in establishing the welding procedure.

The specifications do not include chemical requirements for the different classes; however, when bars are purchased from the mill, the mill will provide a chemical analysis report of the bars, if requested. The grade number is the indication of the strength of the bars and the numbers indicate the yield point in thousand pounds per square inch minimum. All bar sizes are not made in all grades and it is only the specification A615 that provides the large No. 14 and No. 18 size bars.

It is necessary to splice concrete reinforcing bars in all but the most simple concrete structures. In the past, splicing was done by overlapping the bars from 20 to 40 diameters and wiring them together and relying on the surrounding concrete to transmit the load from one bar to the other. This method is wasteful of the steel and is sometimes impractical. Welding is now used for splicing concrete reinforcing bars. Three welding processes are used for the majority of welding splices; however, several of the other processes can be used. There is a mechanical splice similar to welding which utilizes medium-strength metal cast (*metallic grout*) around the ends of the bars

FIGURE 18-4 Summary of information for reinforcing bars.

ASTM Specification	Specification Identification	Grades Produced	Grade Identification	Size Designation Bar Number	Strength		Composition (1)	
					Tensile min psi	Yield min psi	Carbon	Manganese
A-615 (New billet steel)	N	40	Blank	#3 thru #11 and #14 and #18	70,000	40,000	-	-
		60	60		90,000	60,000		
		75	75		100,000	75,000		
A 616 (Made from A 1)		50	Blank	#3 thru #11	80,000	50,000	0.55 0.82	0.60-1.00
		60	60		90,000	60,000		
A 617 (Made from A 21)	A	40	Blank	#3 thru #11	70,000	40,000	0.40-0.59	0.60-0.90
		60	60		90,000	60,000		

Note: See specific ASTM specification for additional information—
(1) composition based on A-1 and A-21

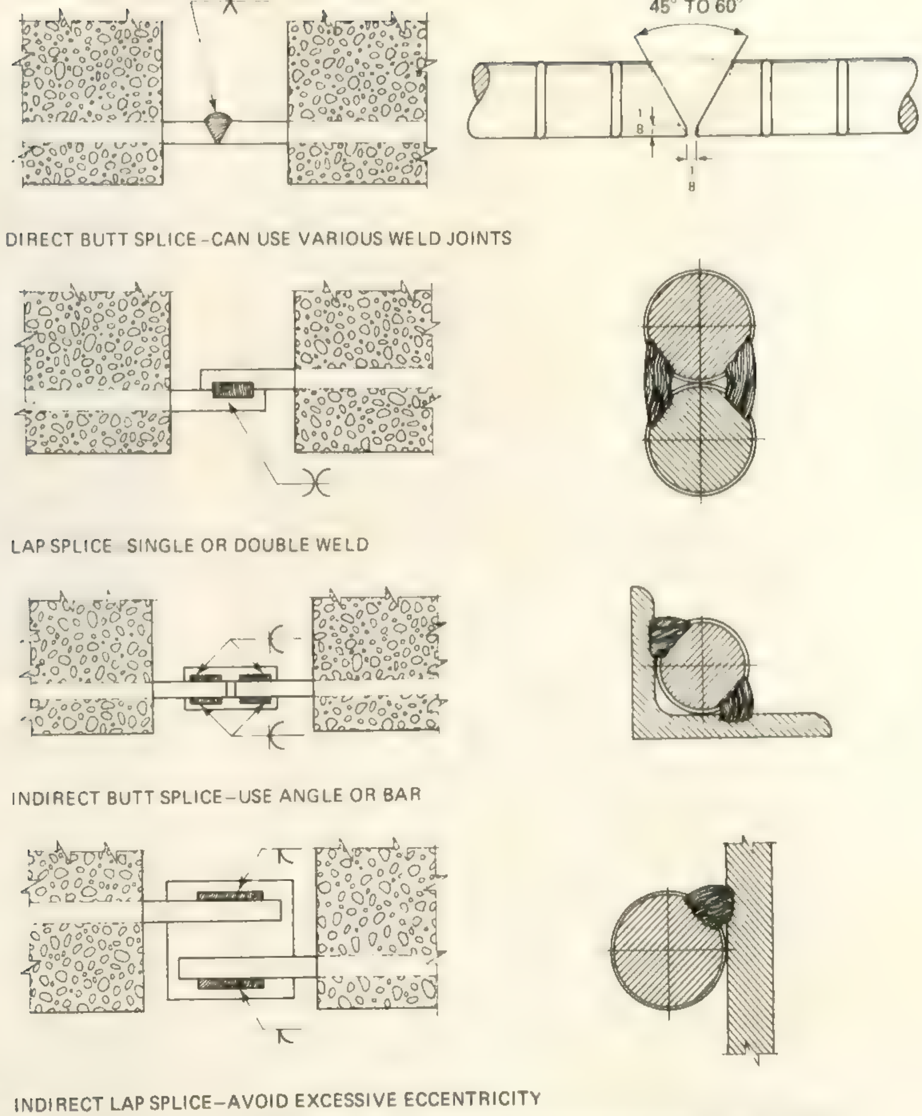


FIGURE 18-5 Types of reinforcing bar spl

enclosed within a steel sleeve having internal grooves. The welding processes most commonly used are shielded metal arc welding, gas metal arc welding, and thermit welding. It was mentioned previously that there are no chemistry requirements for the three ASTM specifications. However, the reinforcing bars of specification A616 rail steel are produced from used railroad rails which were originally made to specification A1. Old railroad rails are salvaged and heated and cut into three parts, the flange, the web, and the head. The heads are then rolled into the deformed reinforcing bars. ASTM specification A1 has chemical requirements for steel rails and they contain relatively high amounts of carbon and manganese.

The reinforcing bars made to specification A617 are made from salvaged carbon steel axles used for railroad cars. These axles when originally produced were made to specification A21. In this ASTM specification the carbon and manganese is relatively high. These are both considered in the hard-to-weld category of steels. The bars produced to A615 have only a maximum for phosphorus content; however, based on the strength level of steels the alloy content should not be too high. For quality welding it is best to assume that they, too, are in the hard-to-weld category. If at all possible, the analysis of the reinforcing bars should be determined from mill reports. If this is not possible, the bars could be analyzed for exact composition. In lieu of this, it is recommended that the bars be considered to have a carbon equivalent of 0.75, thus in the hard-to-weld category.

The American Welding Society has provided a specification entitled, "Reinforcing Steel Structural Welding Code."[4] This code provides a table of carbon equivalents which relates to the bar size and then presents recommended preheat and interpass temperature. The standard formula for the determination of carbon equivalent is used. There are six carbon equivalents which can be calculated only if the analysis of the reinforcing bars are known.

The code also provides joint design information for making direct butt splices, for making indirect butt splices, and for making lap splices (Figure 18-5). A butt splice is a direct end-to-end splice of bars with their axis

approximately in line and of approximately the same size. A split pipe is often used for backing. An indirect butt splice is one in which an intermediary piece such as a steel plate or rolled angle is used with each reinforcing bar welded directly to the same piece. The lap welded splice is made by overlapping the two bars alongside each other and welding together. Direct splices can be made between bars of different sizes by providing a transition type configuration to aid stress flow. For butt splices when the bars are in the horizontal position the single groove weld is most often used with a 45 to 60° included angle. Double-groove welds can be made in the larger bars. When the bars are to be welded with the axis vertical, a single or double bevel groove weld is used with the flat side or horizontal side on the lower bar. On occasion, the reinforcing bar may need to be welded to other steel members and a variety of weld joints can be used.

This code provides filler metal selection information based on the grade number of the steel. When welding using the shielded metal arc welding process, grade 40, the AWS E-7018, is recommended, for grade 50 the AWS E-8018 is recommended, for grade 60 and the low-alloy A706 the AWS E-9018 electrode is recommended, and for the grade 75 the AWS E-10018 electrode is recommended. If the XX18 is not available, the XX15 or XX16 can be used. In the case of gas metal arc welding, the E-70S electrode would be used and for flux-cored arc welding the E70T type would be used when welding grade 40 bars. If these processes are used, the filler metal must meet the same mechanical properties as the equivalent shielded metal arc welding electrode mentioned.

The code also provides minimum preheat and innerpass temperatures based on the carbon equivalent of the reinforcing bars. It also relates to the size of the bar. It is important to determine the composition of the bar so that the carbon equivalent can be determined. This establishes the heat requirement, which ranges from 50 °F (10 °C) up through 500 °F (260 °C) based on the size of the bar and the carbon equivalent. In the case of large bars and if the carbon equivalent is not known, the 500 °F preheat would be recommended. Consult the code for further information.

The code further requires that joint welding procedures should be established based on the welding process, filler metal type and size, and welding technique, which involves position, joint detail, and so on. Welders must be qualified. A direct butt splice or indirect butt splice specimen is used. The test bars are tested in tension. Figure 18-6 shows a reinforcing bar being welded using the gas metal arc welding process.

The gas metal arc welding process will make the weld in approximately one-half the time required for shielded metal arc covered electrodes. Welding is highly recommended as the way to splice reinforcing bars. The welded splices will exceed the strength of lapped and wired splices. It will also exceed a strength level of the cast metal splices which are sufficiently strong to withstand the strength level of the reinforced concrete composite structure.

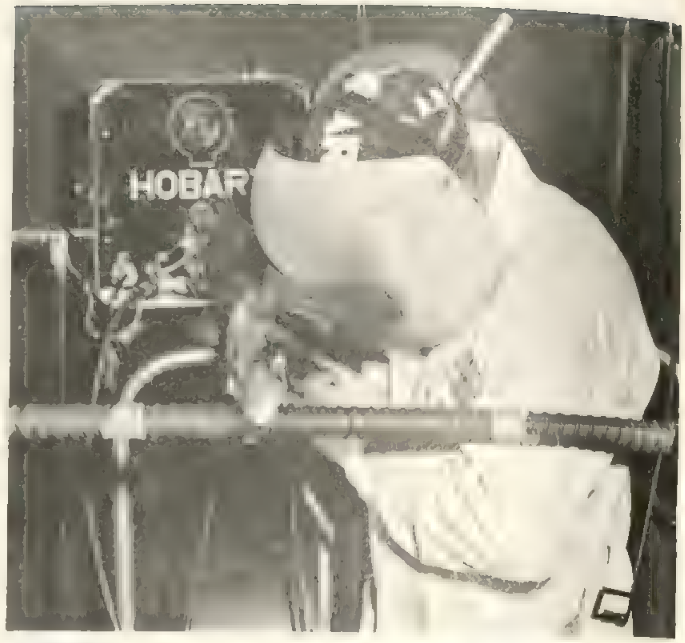


FIGURE 18-6 Joining bars with GMAW.

18-4 COATED STEELS

The coated steel that will be discussed in detail is galvanized or zinc-coated sheet steel. Galvanized steel is widely used and is becoming increasingly important. Manufacturers of many items such as truck bodies, buses, and automobiles are increasingly concerned with the effects of corrosion particularly when chemicals are used on roads for ice control. Galvanized metal is also used in many appliances, such as household washing machines and driers, and in many industrial products, such as air conditioning housings and processing tanks. Other uses for galvanized products are for high-tension electrical transmission towers, highway sign standards, and protective items.

There are two methods of galvanizing steel. One is by coating sheet metal and the other is by hot dipping the individual item. The coated sheet metal is produced by the continuous hot dip process. The continuous hot-dip or zinc-coated sheet comes in different classes based on the thickness of the zinc coating. The coating varies from 1 to 1.75 oz of zinc per square foot of the surface, based on coating both sides of the sheet. One-side-coated steel is also available. Hot-dipped individual parts have coatings exceeding the thickness mentioned above. Welding of zinc-coated steel can be done, with specific precautions. When galvanized steel is arc welded the heat of the welding arc vaporizes the zinc coating in the weld

area. The zinc volatilizes and leaves the base metal adjacent to the weld. The extent to which the coating is disturbed depends on the heat input of the arc and the heat loss from the base metal. The disturbed area is greater with the slower welding speed processes such as gas tungsten arc welding.

When galvanized sheet is resistance welded, the welding heat causes less disturbance of the zinc coating than the arc processes. The resistance to corrosion or rather the protection by the zinc is not disturbed since the zinc forced from the spot weld will solidify adjacent to the spot weld and protect the weld nugget. Resistance welding of galvanized steel is more of a problem because of the zinc pickup of the welding tips and tools.[5]

Weld Quality

The zinc in the gaseous state may become entrapped in the molten weld metal as it solidifies. If this occurs, there will be porosity in the weld metal and if sufficient zinc is available it will cause large voids in the surface of the deposit. The presence of the zinc in stressed welds can cause cracking and it may also cause delayed cracking due to stress corrosion. To eliminate this, the weld joint must be designed to allow the zinc vapor to completely escape from the joint. Fixturing, backing straps, and so on, should be arranged to allow for the zinc to escape completely. Other ways to avoid zinc entrapment in weld metal is to use sufficient heat input when making the weld. It is also important to secure complete and full penetration of the joint. The ultimate precaution would be to remove the zinc from the area to be welded.

When welding on galvanized steel or any coated steel, particularly those with coatings that produce noxious fumes, positive ventilation must be provided. Positive ventilation involves the use of a suction hose at the weld area. When using the gas metal arc process or the flux-cored arc process, suction-type gun nozzles should be used. Welding on zinc or other coated steels should never be done in confined areas.

For corrosion resistance of the weld it is advisable to use a corrosion-resistant weld metal, such as a copper–zinc alloy or a stainless steel. In any case, when arc welding is used the area adjacent to the weld will lose the protective zinc coating which must be repaired.

Arc Welding

The electrode selection should be based on the thickness of metal and the position that will be used when welding galvanized steel. The EXX12 or 13 will be used for welding thinner material, the EXX10 or 11 will be used for welding galvanized pipe and for welding hot-dipped galvanized parts of heavier thickness. The low-hydrogen electrodes can also be used on heavier thickness. The welding technique should utilize slow travel speed to permit degassing of the molten metal. The electrode should point forward to force the zinc vapor ahead of the arc. The quality of welds will be equal to those of bare metal, assuming the weldability of the steel is equal.

The gas metal arc welding process is widely used for joining galvanized steel. For the thinner gauges the fine-wire short-circuiting method is recommended. In this case, the technique would be similar to that used for bare metal. The shielding gas can be 100% CO_2 or the 75% argon and 25% CO_2 mixture. The selection is dependent on the material thickness and position of welding. For certain applications, the argon–oxygen mixture is used. The amount of spatter produced when welding galvanized steel is slightly greater than when welding bare steel. The gun tip and nozzle shoud be cleaned more often. The electrode wire should be of the highly deoxidized type; however, a stainless steel or bronze type can be employed. This will produce a weld deposit that will be corrosion resistant.

The flux-cored arc welding process can be used for galvanized steel. It is recommended for the heavy gauges and on hot-dipped galvanized parts. The highly deoxidized type of welding electrode should be used.

The gas tungsten arc welding process is not popular since it causes a larger area of zinc adjacent to the weld to be destroyed. In addition, the volatilized zinc is apt to contaminate the tungsten electrode and require frequent redressing. To overcome this, extra high gas flow rates are used, which can be expensive. If a filler rod is used it should be of either the highly deoxidized steel type or of the bronze type. In this case the arc is played on the filler rod and zinc contamination of the tungsten electrode is reduced.

The carbon arc welding process can be used for welding galvanized steel. Both the single carbon torch and twin carbon torch can be used. When the single carbon is used the arc is played on the filler rod and extremely high rates of speed can be attained. Normally in this situation the filler rod is the 60% copper–40% zinc alloy, type RBCuZn-A. By directing the arc on the filler rod it melts and sufficient heat is produced in the base metal for fusion but not sufficient to destroy the zinc coating. This process and technique is used in the sheet metal industry for ductwork.

Torch Brazing

The oxyacetylene torch is used for brazing galvanized steel. The technique is similar to that mentioned with the carbon arc. The flame is directed toward the filler rod, which melts and then fills the weld joint. A generous quantity of brazing flux is used to help reduce the zinc loss adjacent to the weld.

Repairing the Zinc Coating

The area adjacent to the weld may be free of zinc because of the high temperature of the weld. To produce a corro-

sion-resistant joint, the zinc must be replaced in this area. There are several ways of replacing the zinc. One is by the use of zinc base paste sticks sometimes called zinc sticks or galvanized sticks sold under different proprietary names. These sticks are wiped on the heated bare metal. With practice a very good coating can be placed which will blend with the original zinc coating. This coating will be thicker than the original coating, however. Another way of replacing the depleted zinc coating is by means of flame spraying using a zinc spray filler material. This is a faster method and is used if there is sufficient zinc coating to be replaced. The coating should be two to two-and-one-half times as thick as the original coating for proper corrosion protection.

Other Coated Metals

One other coated metal that is often welded is known as tern plate. This is sheet steel hot dipped with a coating of a lead-tin alloy. The tern alloy is specified in thicknesses based on the weight of tern coating per square foot of sheet metal. This ranges from 0.35 to 1.45 oz per square foot of sheet metal based on both sides being coated. Tern plate is often used for making gasoline tanks for automobiles. It is welded most often by the resistance welding process. If it is arc welded or oxyacetylene welded the tern plating is destroyed adjacent to the weld and it must be replaced. This can be done similar to soldering.

Aluminized steel is also widely used in the automobile industry particularly for exhaust mufflers. In this case, a high-silicon-aluminum alloy is coated to both sides of the sheet steel by the hot dip method. There are two common weights of coating, the regular is 0.40 oz/ft^2 and the lightweight coating is 0.25 oz/ft^2 based on coating both sides of the sheet steel. If an arc or gas weld is made on aluminum-coated steel the aluminum coating is destroyed. It is relatively difficult to replace the aluminum coating; therefore, painting is most often used.

18-5 OTHER METALS

This section includes special steels not covered previously. These metals are abrasion-resisting steel, free-machining steel, manganese steel, silicon steel, and wrought iron.

Abrasion-Resisting Steel

Abrasion-resisting (AR) steel is carbon steel usually with a high-carbon analysis, used as liners in material-moving systems and for construction equipment, where severe abrasion and sharp hard materials are encountered. Abrasion-resisting steels are often used to line dump truck bodies for quarry service, for lining conveyors, chutes, bins, and so on. The abrasion-resisting steel is not used for structural strength purposes, but only to provide lining materials for wear resistance. Steel companies make different proprietary alloys that all have similar properties and, in general, similar compositions. Most AR steels are high-carbon steel in the range 0.80 to 0.90% carbon; however, some are low carbon with multiple alloying elements. These steels are strong and have a hardness up to 40 Rockwell C or 375 BHN. Abrasion-resisting bars or plates are welded to the structures and when worn out are removed by oxygen cutting or air carbon arc and new plates installed by welding.

Low-hydrogen welding processes are required. Local preheat of 400°F (204°C) is advisable to avoid underbead cracking of the base metal or cracking of the weld. In some cases this can be avoided by using a preheat weld bead on the carbon steel structure and filling in between the bead and the abrasion-resisting steel with a second bead in the groove provided. The first bead tends to locally preheat the abrasion-resisting steel to avoid cracking and the second bead is made having an oversized throat. Intermittent welds are made since continuous or full-length welds are usually not required. Efforts should be made to avoid deep weld penetration into the abrasion-resisting steel so as not to pick up too much carbon in the weld metal. If too much carbon is picked up the weld bead will have a tendency to crack.

When using the shielded metal arc welding process the EXX15, EXX16, or EXXX8 electrodes are used. When using gas metal arc welding the low penetrating type shielding gases such as the 75% argon-25% CO_2 mixture should be used. The flux-cored arc welding process is used and the self-shielding version is preferred since it does not have the deep penetrating quality as the CO_2 shielded version. During cold weather applications, it is recommended that the abrasion-resistant steel be brought up to 100°F (38°C) temperature prior to welding.

Free-Machining Steels

The term *free machining* can apply to many metals but it is normally associated with steel and brass. Free machining is the property that makes machining easy because small cutting chips are formed. This characteristic is given to steel by sulfur and in some cases by lead. It is given to brass by lead. Sulfur and lead are not considered alloying elements. In general, they are considered impurities in the steel. Lead is purposely added to steel to give it free-machining properties.

Free-machining steels are usually specified for parts that require a considerable amount of machine tool work. The addition of the sulfur makes the steel easier to turn, drill, mill, and so on, even though the hardness is the same as a steel of the same composition without the sulfur.

The sulfur content of free-machining steels will range from 0.07 to 0.12% to as high as 0.24 to 0.33%. The amount of sulfur is specified in the AISI specifica-

tions for carbon steels. Sulfur is not added to any of the alloy steels. Leaded grades comparable to 12L14 and 11L18 are available. Unless the correct welding procedure is used, the weld deposits on free-machining steel will be porous and will not provide properties normally expected.

The basis for establishing a welding procedure for free-machining steels is the same as that required for carbon steels of the same analysis. These steels usually run from 0.010% carbon to as high as 1.0% carbon. They may also contain manganese ranging from 0.30% to as high as 1.65%. Therefore, the procedure is based on these elements. In the case of shielded metal arc welding, use a low-hydrogen electrode of the EXX15, EXX16, or EXXX8 classification. In the case of gas metal arc or flux-cored arc welding the same type of filler metal is specified as is normally used. Submerged arc welding would not normally be used on free-machining steels. Gas tungsten arc welding is not normally used.

The welding procedure should minimize dilution of base metal with the filler metal. Efforts should be made to reduce penetration so as to melt less sulfur or lead. This means using lower welding currents.

Free-machining steel can be successfully welded and quality welds made; however, the procedures are slower. For this reason, free-machining steel should not be specified for weldments unless absolutely necessary.

Manganese Steel

Manganese steel is sometimes called austenitic manganese steel because of its metallurgical structure. It is also called Hadfield manganese steel after its inventor. It is an extremely tough, nonmagnetic alloy. It has an extremely high tensile strength, a high percentage of ductility, and excellent wear resistance. It also has a high resistance to impact and is practically impossible to machine.

Hadfield manganese steel is widely used as castings but is also available as rolled shapes. Manganese steel is popular for impact wear resistance. It is used for railroad frogs, for steel mill coupling housings, pinions, spindles, and for dipper lips of power shovels operating in quarries. It is also used for power shovel track pads, drive tumblers, and dipper racks and pinions.

The composition of austenitic manganese is from 12 to 14% manganese and 1 to 1.4% carbon. The composition of cast manganese steel would be 12% manganese and 1.2% carbon. Nickel is often added to the composition of the rolled manganese steel.

A special heat treatment is required to provide the superior properties of manganese steel. This involves heating to 1850°F (1008°C) followed by quenching in water. In view of this type of heat treatment and the material toughness, special attention must be given to welding and to any reheating of manganese steel.

Manganese steel can be welded to itself and defects can be weld repaired in manganese castings. Manganese steel can also be welded to carbon and alloy steels and weld surfacing deposits can be made on manganese steels.

Manganese steel can be prepared for welding by flame cutting; however, every effort should be made to keep the base metal as cool as possible. If the mass of the part to be cut is sufficiently large it is doubtful if much heat will build up in the part sufficient to cause embrittlement. However, if the part is small, it is recommended that it be frequently cooled in water or, if possible, partially submerged in water during the flame cutting operation. For removal of cracks the air carbon arc process can be used. The base metal must be kept cool. Cracks should be completely removed to sound metal prior to rewelding. Grinding can be employed to smooth up these surfaces.

There are two types of manganese steel electrodes available. Both are similar in analysis to the base metal but with the addition of elements which maintain the toughness of the weld deposit without quenching. The EFeMn-A electrode is known as the nickel–manganese electrode and contains from 3 to 5% nickel in addition to the 12 to 14% manganese. The carbon is lower than normal manganese, ranging from 0.50 to 0.90%. The weld deposits of this electrode on large manganese castings will result in a tough deposit due to the rapid cooling of the weld metal.

The other electrode used is a molybdenum–manganese steel type EFeMn-B. This electrode contains 0.6 to 1.4% molybdenum instead of the nickel. This electrode is less often used for repair welding of manganese steel or for joining manganese steel itself or to carbon steel. The manganese nickel steel is more often used as a buildup deposit to maintain the characteristics of manganese steel when surfacing is required.

Stainless steel electrodes can also be used for welding manganese steels and for welding them to carbon and low-alloy steels. The 18–8% chrome–nickel types are popular; however, in some cases when welding to alloy steels the 29–9% type is sometimes used. These electrodes are considerably more expensive than the manganese steel electrode and are not popular.

When welding manganese steel with manganese type electrodes the welds should be made with relatively low current and they should be peened with a pneumatic hammer as quickly as possible. This helps spread or deform the deposited weld metal and avoids triaxial shrinkage stresses, which can cause cracking. The base metal should be kept cool. Small parts must be cooled frequently or partially submerged in water. The manganese steel electrodes are available both as covered electrodes and as bare electrodes. Bare electrodes are not popular. Covered electrodes and bare electrodes are operated with the electrode positive on direct current. Preheating is never employed when welding manganese steels, and should the part become heated to over 500°F (260°C) it must be reheat-treated to retain its toughness.

Silicon Steel

Silicon steels, or, as they are sometimes called, electrical steels, are steels that contain from 0.5% to almost 5% silicon but with low carbon and low sulfur and phosphorus. Silicon steel is provided primarily as sheet or strip. The silicon steels are designed to have lower hysteresis and eddy current losses than plain steel when used in magnetic circuits. Their magnetic properties make silicon steels useful in direct-current fields for most applications. Silicon steel stampings are used in the laminations of electric motor armatures, rotors, and generators. They are widely used in transformers for the electrical power industry and for transformers, chokes, and other components in the electronics industry.

Welding is important to silicon steels since many of the laminations are assembled in packs which are welded together. Figure 18-7 shows an example of welding a stack of laminations. Welds are made on the edge of each sheet to hold the stack together. Welding is done instead of punching holes and riveting the laminations in order to reduce manufacturing costs. Almost all the arc welding processes are used. The more popular processes are gas metal arc using CO_2 for gas shielding and gas tungsten arc and plasma arc. When the consumable electrode processes are used the stampings are usually indented to allow for deposition of filler metal. For gas tungsten arc and plasma arc the filler metals are not used and the edges are fused. The size of the weld bead should be kept minimum so that eddy currents are not conducted between laminations in the electrical stack.

One precuation that should be taken in welding silicon steel laminations is to make sure that the laminations are tightly pressed together and that all the oil used for protection and used in manufacturing is at a minimum. Oil can cause porosity in the welds, which might be detrimental to the lamination assembly.

Wrought Iron

Wrought iron is a ferrous material made of highly refined iron with slag minutely and uniformly distributed throughout. The slag is a form of stringers that are in a longitudinal arrangement in the finished product. Wrought iron has been used for structural applications and for pipe. It provides good corrosion resistance and has been used for piping systems such as hot water coils for radiant heating and brine coils, for cooling ice rinks, and so on. It is also used for certain architectural applications.

Many applications of so-called "wrought iron" are actually made of mild low-carbon steel. Very little wrought iron is manufactured in the United States today; however, welding is sometimes required for repair or modifications of existing systems.

Wrought iron should be treated exactly the same as low-carbon mild steel and the same welding processes,

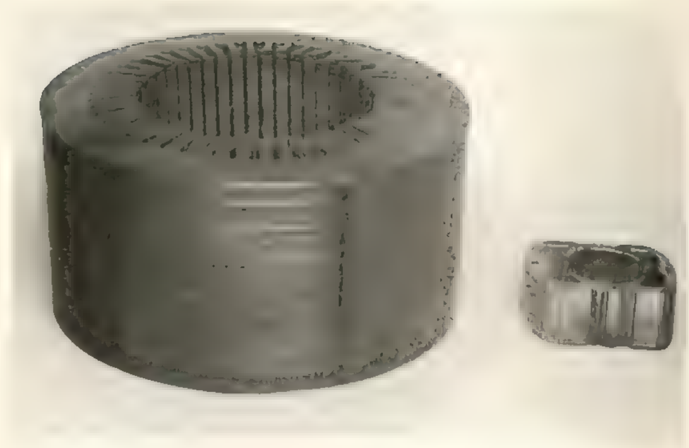


FIGURE 18-7 Welded laminations stack of silicon steels.

procedures, and filler metals should be employed. For welding small wrought iron pipe the oxyacetylene process should be used.

18-6 CLAD METALS

Most clad metals have a cladding metal such as stainless steel, nickel and nickel alloys, or copper and copper alloys welded to a backing material of either carbon or alloy steel. The two metals are welded together at a mill in a roll under heat and pressure. The clad composite plates are usually specified in a thickness of the cladding, which ranges from 5% to 20% of the total composite thickness. The advantage of composite material is to provide the benefits of an expensive material which can provide corrosion resistance, abrasion resistance, and other benefits with the strength of the backing metal. Clad metals were developed in the early 1930s and one of the first used was nickel bonded to carbon steel. This composite was used in the construction of tank cars. Other products made of clad steels are heat exchangers, tanks, processing vessels, materials-handling equipment, storage equipment, and so on.

Clad or composites can be made by several different welding manufacturing methods. The most widely used process is roll welding which employs heat and roll pressure to weld the clad to the backing steel. Explosive welding is also used and weld surfacing or overlay is another method of producing a composite material.

Clad steels can have as the cladding material chromium steel in the range 12 to 15%, stainless steels primarily of the 18–8% and 25–12% analysis, nickel-base alloys such as Monel and Inconel, copper–nickel, and copper. The backing material is usually high-quality steel of the ASTM A285, A212, or similar grade. The tensile strength of clad material depends on the tensile strength of its components and their ratio to its thickness. The clad thickness is uniform throughout the cross section, and the weld between the two metals is continuous throughout.

A different procedure is used for oxygen cutting of clad steel. All of the clad metals mentioned above can be oxygen flame cut with the exception of the copper-clad composite material. The normal limit of clad plate cutting is when the clad material does not exceed 30% of the total thickness. However, a higher percentage of cladding may be cut in thicknesses of ½ in. (12 mm) and over. The oxygen pressure is lower when cutting clad steel; however, larger cutting tips are used. The quality of the cut is very similar to the quality of the cut of carbon steel. When flame cutting clad material the cladding material must be on the underside so that the flame will first cut the carbon steel. The addition of iron powder to the flame will assist the cutting operation. Schedules of flame cutting are provided by clad steel producers as well as flame cutting equipment producers. For oxygen flame cutting copper and copper–nickel clad steels the copper clad surface must be removed and the backing steel cut in the same fashion as bare carbon steel. Copper and brass clad plate can be cut using iron powder cutting. Clad steels can be fabricated by bending and rolling, shearing, punching, and machining in the same manner as the equivalent carbon steels. Clad materials can be preheated and given stress relief heat treatment in the same manner as carbon steels. However, stress-relieving temperatures should be verified by consulting with the manufacturer of the clad material.

Welding Clad Steels

Clad materials can be successfully welded by adopting special joint details and following special welding procedures. Inasmuch as the clad material is utilized to provide special properties, it is important that the weld joint retain these same properties. It is also important that the structural strength of the joint be obtained with the quality welds of the backing metal.

The normal procedure for making a butt joint in clad plate is to weld the backing or steel side first with a welding procedure suitable for the base material being welded. Then the clad side is welded with the suitable procedure for the material being joined. This sequence is preferable to avoid the possibility of producing hard brittle deposits, which might occur if carbon steel weld metal is deposited on the clad material. Different joint preparations can be used to avoid the possible pickup of carbon steel in the clad alloy weld. Any weld joint made on clad material should be a full-penetration joint. When designing the joint details it is wise to make the root of the weld the clad side of the composite plate. This may not always be possible; however, it is more economical since most of the weld metal can be of the less expensive carbon steel rather than the expensive alloy clad metal. This is shown in Figure 18-8 as the preferred type of joint. If the material is of sufficient thickness that a double-groove weld is required, it is recommended that the smaller groove side be the clad side. For material $\frac{3}{16}$ in. (4.8 mm) or thinner, a square groove joint detail should be used.

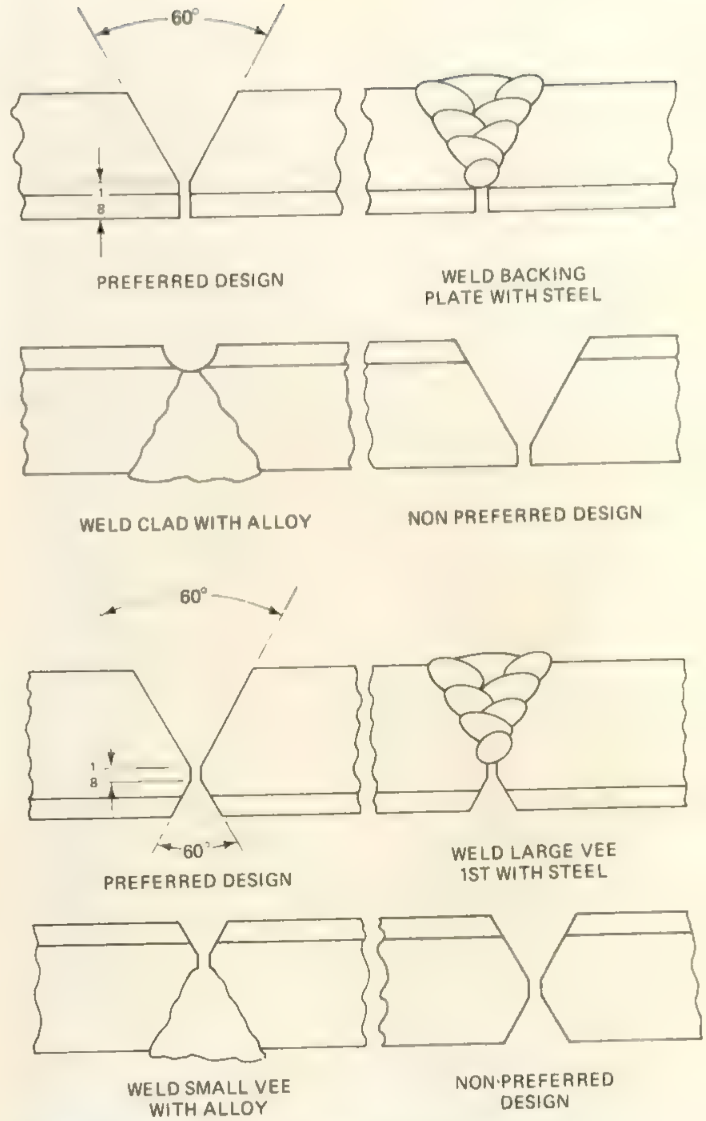


FIGURE 18-8 Weld joint design for clad plate.

The selection of the welding process or processes used would be based on welding the material in the thickness and position required. Shielded metal arc welding is probably used more often; however, submerged arc welding is used for fabricating large thick vessels, and the gas metal arc welding process is used for medium thicknesses; the flux-cored arc welding process is used for the steel side, and gas tungsten arc welding is sometimes used for the thinner materials, particularly the clad side. It is important to select a process that will avoid penetrating from one material into the other. The welding procedure should be designed so that the clad side is joined using the appropriate process and filler metal to be used with the clad metal and the backing side should be welded with the appropriate process and filler metal recommended for the backing metal. Exceptions

to this will be covered later. For code work the welding procedure must be qualified in accordance with the specification requirements.

The backing side or steel side would be welded first. The depth of the penetration of the root pass must be closely controlled. It is desirable to produce a root pass which will penetrate through the root of the backing metal weld joint into the root face area, yet not come in contact with the clad metal. If penetration is excessive and the root bead melts into the clad material because of poor fitup or any other reason the deposit will be brittle. If this occurs, the weld will have to be removed and remade. However, if the penetration of the backing steel root bead is insufficient, the amount of back gouging will be excessive and larger amounts of the clad material weld metal will be required. The steel side of the joint should be welded at least halfway prior to making any of the weld on the clad side. If warpage is not a factor, the steel side weld can be completed before welding is started on the clad side.

The clad side of the joint is prepared by gouging to sound metal or into the root pass made from the backing steel side. This can be done by air carbon arc gouging or by chipping. The gouging should be sufficient to penetrate into the root pass so that a full penetration of the joint will result. This will determine the depth of the gouging operation. It is also a measure of the depth of penetration of the root pass. Grinding is not recommended since it tends to wander from the root of the joint and may also cover up an unfused root by smearing the metal. If the depth of gouging is excessive, weld passes made with the steel electrode may be required to avoid using an excessive amount of clad metal electrode.

On thin materials the gas tungsten arc welding process may be used; on thicker materials shielded metal arc or gas metal arc may be used. The filler metal must be selected to be compatible with the clad metal analysis. There is always the likelihood of diluting the clad metal deposit by too much penetration into the steel backing metal. Special technique should be used to minimize penetration into the steel backing material. This is done by directing the arc on the molten puddle instead of on the base metal. When welding copper or copper-nickel clad steels a high-nickel electrode is recommended for the first pass (ECuNi or ENi-l). The remaining passes of the joint in the clad metal should be welded so that the copper or copper-nickel electrode matches the composition of the clad metal.

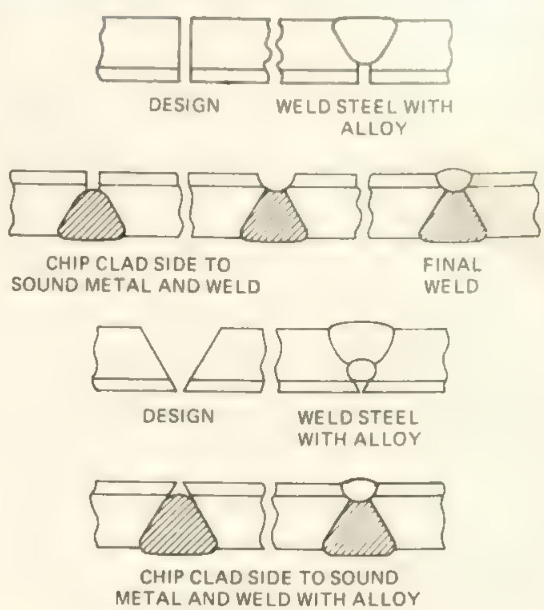
When the clad metal is stainless steel, the initial pass which might fuse into the carbon steel backing should be of a richer analysis of alloying elements than necessary to match the stainless cladding. This same principle is used when the clad material is Inconel or Monel. The remaining portion of the clad side weld should be made with the electrode compatible with or having the same analysis as the clad metal. The procedure should be designed so that the final weld layer will have the same composition as the clad metal.

On heavier thicknesses, where the weld of the backing steel is made from both sides, it is important to avoid allowing the steel weld metal to come in contact or to fuse with the clad metal. This will cause a contamination of the deposit which may result in a brittle weld.

When welding thinner gauge clad plate and inside clad pipe it may be more economical to make the complete weld using the alloy weld metal compatible with the clad metal instead of using two types of filler metal. The alloy filler metal must be compatible with the steel backing metal. The expense of the welding filler metal may be higher, but the total weld joint may be less expensive because of the more straightforward procedure. Joint preparation may also be less extensive using this procedure. For medium thickness, the joint preparation is a single vee or bevel without a large root face. The root face is obtained by grinding the feather edge to provide a small root face. If possible, the face of the weld will be the steel or backing side of the joint. The backing side or steel side is welded first using the small-diameter electrode for the root pass to ensure complete penetration. The remainder of the weld is made on the steel side. The weld is completed by chipping the back side or clad side of the joint and making a final pass from that side (Figure 18-9).

If the composite is a pipe or if it must be welded from one side, the *buttering* technique should be used. In this case the filler metal must provide an analysis equal to the clad metal and be compatible with the backing steel. Weld passes are made on the edge of the composite to butter the clad and backing metal. The buttering pass

FIGURE 18-9 Alloy weld from both sides.



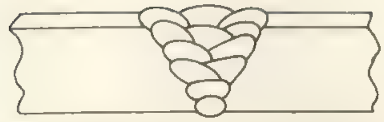


FIGURE 18-10 Alloy weld from clad side.

must be smoothed to the design dimensions prior to fitup. The same electrode can be used to make the joint.

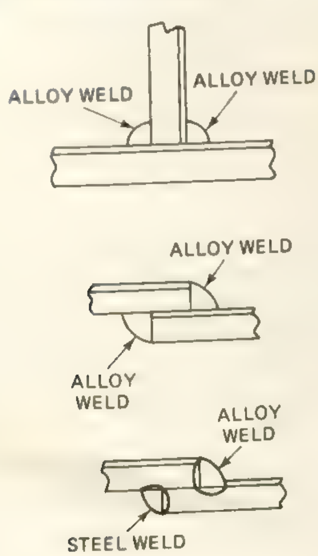
When the joint is welded from the clad side the procedure is the same. The filler metal deposit must match the clad metal but be compatible with the backing metal (Figure 18-10). The same basic joint procedure can be used for flat, vertical, horizontal, or overhead weld joints.

When welding heavy, thick composite plate the U-groove weld joint design is recommended instead of the V groove, to minimize the amount of weld metal.

When the submerged arc welding process is used for the steel side of the clad plate, caution must be exercised to avoid penetrating into the clad metal. This same caution applies to automatic flux-cored arc welding or gas metal arc welding. A larger root face is required and fitup must be very accurate in order to control root bead penetration.

The submerged arc process can also be used on the clad side when welding stainless alloys. However, caution must be exercised to minimize dilution of a high-alloy material with the carbon steel backing metal. The proper filler metal and flux must be utilized. To minimize admixture of the final pass, it is recommended that the clad side be welded with at least two passes so that dilution would be minimized in the final pass. When making T joints, corner joints, or lap joints special precautions must be taken so as to have the weld metal in proper relationship to the clad and the backing material (Figure 18-11).

FIGURE 18-11 Tee and lap joints.



Special quality control precautions must be established when welding clad metals so that undercut, incomplete penetration, lack of fusion, and so on, are not allowed. In addition, special inspection techniques must be incorporated to detect cracks or other defects in the weld joints.

18-7 DISSIMILAR METALS

There are many applications where weldments are made from metals of different compositions. A successful weld between dissimilar metals is one that is as strong as the weaker of the two metals being joined, that is, possessing sufficient tensile strength and ductility so that the joint will not fail. Such joints can be accomplished in a variety of different metals and by many of the welding processes. The problem of making welds between dissimilar metals relates to the transition zone between the metals and the intermetallic compounds formed in this transition zone. For the fusion welding processes it is important to investigate the phase diagram of the two metals involved. If there is mutual solubility of the two metals, the dissimilar joints can be made sucessfully. If there is little or no solubility between the two metals to be joined, the weld joint will not be successful. The intermetallic compounds that are formed, between the dissimilar metals, must be investigated to determine their crack sensitivity, ductility, susceptibility to corrosion, and so on. The microstructure of this intermetallic compound is extremely important. In some cases, it is necessary to use a third metal that is soluble with each metal in order to produce a successful joint.

Another factor is the coefficient of thermal expansion of both materials. If these are widely different, there will be internal stresses set up in the intermetallic zone during any temperature change of the weldment. If the intermetallic zone is extremely brittle, service failure may soon occur.

The difference in melting temperatures of the two metals that are to be joined must also be considered. This is of primary interest when a welding process utilizing heat is involved since one metal will be molten long before the other when subjected to the same heat source. When metals of different melting temperatures and thermal expansion rates are to be joined, the welding process with a high heat input that will make the weld quickly has an advantage.

The difference of the metals on the electrochemical scale is an indication of their susceptibility to corrosion at the intermetallic zone. If they are far apart on the scale, corrosion can be a serious problem.

In certain situations, the only way to make a successful joint is to use a transition material between the two dissimilar metals. An example of this is the attempt to weld copper to steel. The two metals are not mutually soluble, but nickel is soluble with both of them. There-

fore, by using nickel as an intermediary metal the joint can be made. Two methods are used: (1) use a piece of nickel, or (2) deposit several layers of nickel alloy on the steel (i.e., butter or surface the steel with a nickel weld metal deposit). The nickel or nickel deposit can be welded to the copper alloy using a nickel filler metal. Such a joint will provide satisfactory properties and will be successful.

Another method of joining dissimilar metals is the use of a composite insert between the two metals at the weld joint. The composite insert consists of a transition joint between dissimilar metals made by a welding process that does not involve heating. Following is a brief description of some of the welding processes that can be used for making composite inserts.

Explosion welding is used to join many so-called incompatible metals. In explosion welding the joint properties will be equal to those of the weaker of the two base materials. Since minimum heat is introduced there is minor melting and no thermal compounds are formed. The characteristic sine wave pattern of the interface greatly increases the interface area. Composites containing a transition joint are commercially available between aluminum and steel, aluminum and stainless steel, aluminum and copper, and other materials.

Cold welding is used for making dissimilar metal transition joints. This process does not use heat and thus avoids the heat-affected zone and the intermetallic fusion alloy. Little or no mixing of the base metals takes place. It is commonly used to join aluminum to copper.

Ultrasonic welding is used for welding dissimilar metals since very little heat is developed at the weld joint. Ultrasonic welding can be used only for very thin materials or small parts.

Friction welding is used for joining dissimilar metals and for making composite transition inserts. Various dissimilar combinations have been welded, including steel to copper-base alloys, steel to aluminum, stainless to nickel-base alloys, and so on. In friction welding only a very small amount of the base metal is heated and that which is melted is thrown from the joint; therefore, the intermetallic material is kept to a very minimum. The heat-affected zone is also minimal.

The high-frequency resistance process is also widely used for dissimilar metal welding. Here the heat is concentrated on the very surface of the parts being joined and pressure applied is sufficient to make welds of many dissimilar materials. It can be used for joining copper to steel at very high speeds.

Diffusion welding is widely used for aerospace applications of dissimilar metals welding. Percussion welding is also used but this process is restricted to wires or small parts. The laser beam welding process has also been used.

The electron beam welding process has had wide application for joining dissimilar metals. Electron beam uses high-density energy and fast welding speed. It seems to overcome the difference of thermal conductivity when welding metals together having wide variation of thermal conductivity. In addition, the weld zone is extremely small and filler metal is not introduced. Since there is such a small amount of intermetallic compound formed electron beam does offer an advantage for many dissimilar combinations.

The flash butt welding process will make high-quality welds between copper and aluminum. With proper controls all or most of the molten metal is forced out of the joint and the weld is complete as a solid-state process. Flash butt welds are made in rods, wires, bars, and tubes.

Arc Welding Dissimilar Metals

The three popular arc welding processes are most often utilized: shielded metal arc, gas tungsten arc, and gas metal arc welding. The popular combinations of dissimilar metals that are joined are shown in Figure 18-12. The table summarizes the requirement to join aluminum to different metals, copper and copper alloys to different metals, nickel alloys to different metals, stainless steel to carbon steels, and the welding together of various types of steels. All these combinations can be successfully welded using the correct procedures.

Welding Aluminum to Different Metals

There is a wide difference between the melting temperature of aluminum, approximately 1200 °F (649 °C), and of steel, approximately 2800 °F (1538 °C). The aluminum will melt and flow away well before the steel has melted. The aluminum iron phase diagram shows that a number of complex brittle intermetallics are formed. It is found that iron–aluminum alloys containing more than 12% iron have little or no ductility. There is wide difference in the coefficient of linear expansion, in thermal conductivity, and in specific heats of aluminum and steel. This will introduce thermal stresses of considerable magnitude.

The most successful method is to use an aluminum–steel transition insert with each metal welded to its own base metal using any of the three arc welding processes.[6]

The other way is to coat the steel surface with a metal compatible with aluminum. A coating of zinc on steel can be used and the aluminum welded to it by the gas tungsten arc welding process. A high-silicon-aluminum filler wire should be used. Direct the arc toward the aluminum; pulsing will assist the welder.

For welding aluminum to stainless steel transition inserts are available. It is also possible to use the coating technique. A coating for the stainless steel is pure aluminum coating, which can be applied by dipping clean stainless steel into molten aluminum. Another way to ob-

Base Metal Combinations	Welding Process and Filler Metal		
	SMAW	GTAW	GMAW
Aluminum to mild and low-alloy steel	Use a transition insert of these metals or coat the surface of the steel and GTAW		
Aluminum to stainless steel	Use a transition insert of these metals or coat the surface of the SS and GTAW		
Aluminum to copper	Use a transition insert of these metals		
Copper to mild and low-alloy steel	ECu	RCu	ECu
Copper to stainless steel	ECuAl-A2	RCuAl-A2	ECuAl-A2
Brass to mild and low-alloy steel	ECuAl-A2	RCuAl-A2	ECuAl-A2
Aluminum bronze to low-alloy steel	ECuAl-A2	RCuAl-A2	ECuAl-A2
Inconel to mild and low-alloy steel	ENiCrFe-3	RNiCrFe-3	ENiCrFe-3
Inconel to austinitic stainless steel	ENiCrFe-3	RNiCrFe-3	ENiCrFe-3
Inconel to ferritic stainless steel	ENiCrFe-3	RNiCrFe-3	ENiCuFe-3
Monel to mild and low-alloy steel	ENiCu-2	RNiCu-2	ENiCu-2
Monel to austinitic stainless steel	ENiCu-2	RNiCu-2	ENiCu-2
Monel to ferritic stainless steel	ENiCu-2	RNiCu-2	ENiCu-2
Ferritic stainless steel to mild and low-alloy steel	ENiCrFe-3	RNiCrFe-3	ENiCrFe-3
Austinitic stainless steel to mild and low-alloy steel	ENiCRFe-3	RNiCrFe-3	ENiCrFe-3
Alloy steel to mild and low-alloy steel	E7018	E70S-X	E70S-X
Q and T steel to mild and low-alloy steel	E7018	E70S-X	E70S-X

FIGURE 18-12 **Popular dissimilar metal combinations.**

tain a compatible coating is by tinning the stainless steel with a high-silicon–aluminum alloy. The aluminum surface can then be gas tungsten arc welded to the aluminum. The arc should be directed toward the aluminum; pulsing will assist the welder. The welding of aluminum to copper is accomplished by using a copper–aluminum transition insert piece.

Welding Copper to Various Metals

Copper and copper-base alloys can be welded to mild and low-alloy steels and to stainless steels. For thinner sections, the gas tungsten arc welding process can be used with a high-copper-alloy filler rod. The pulsed mode makes it easier to obtain a good-quality weld. The arc should be directed to the copper section to minimize pickup of iron. In the heavier thicknesses first overlay or butter the steel with the same filler metal and then weld the overlayed surface to the copper. It is important to avoid excessive penetration into the steel portion of the joint since iron pickup in copper alloys creates a brittle material. The copper must be preheated.

Another method is to overlay the copper with a nickel-base electrode. A second overlay or layer is recommended on thicker materials. When making the overlay welds on thick copper, the copper should be preheated to 1000°F (538°C). The overlay or buttered surface of the copper part should be smoothed to provide a uniform joint preparation. The copper part should be preheated to 1000°F (538°C) when making the weld. Effort should be made to minimize dilution of the copper with the nickel electrode. Process selection will depend on equipment available and the thickness of the material being joined. Copper can also be joined to stainless steel, and brass can be joined to mild and low-alloy steels.

Welding Nickel-Base Alloys to Steels

Nickel-base alloys such as Monel and Inconel can be successfully welded to low-alloy steel by using the Monel analysis of filler material when using any of the arc welding processes. In the case of Inconel to mild or low-alloy steel the Inconel base electrode would be used. The same situation applies also to the welding of Inconel or Monel to stainless steels.

Welding Stainless Steels to Various Metals

Most stainless steels can be successfully welded to mild and low-alloy steels. Consideration must be given to the effects of dilution of the weld metal with the two base metals and the different coefficients of thermal expansion of stainless steel and mild or low-alloy steels. The weld metal deposited will tend to pick up alloys from both parts of the joint being welded. The effect of this dilution can be controlled by buttering or overlaying the surface of one of the metals being joined and by selecting the correct electrode or filler material. The weld joint between a slightly ferritic stainless steel and a mild or low-

alloy steel would be hard and brittle if made with a slightly ferritic stainless steel electrode. However, if a fully austenitic stainless steel electrode or filler rod is used the amount of ferrite in the weld metal would be reduced to a tolerable level. The electrode or filler wires normally used would be an E310 electrode or filler rod corresponding to the 310 composition. The stabilized stainless steel electrodes and filler wires should be used. The best selection would be an ENiCr-1, which is a 15% chromium-high-nickel composition. This analysis has an austenitic composition and the weld deposit can tolerate considerable dilution before becoming crack sensitive.

Stainless steel has a coefficient of thermal expansion about twice that of mild or low-alloy steel. During the cooling cycle of the weld the stainless steel side will tend to contract more than the mild steel or low-alloy steel side. This difference in contraction will set up stresses in the weld joint. If the weld joint is subjected to repetitive thermal cycles the resulting stress cycling could cause premature failure of the joint in a manner similar to fatigue fracture. The use of stainless steel for buttering will not solve this situation. The buttering technique is not recommended for those situations in which repetitive thermal cycles are involved. The best solution is to use a high-nickel electrode such as the ENiCr-1 or the ENiCrFe-2 electrodes or the ERNiCrFe-5 or ERNiCr-3 filler wires. The relatively low iron content of these alloys allows minimum iron in the weld which reduces cracking. High-nickel deposits have a thermal expansion coefficient similar to that of the low-alloy steel. Thus the thermal stress will be set up in the weld metal and stainless steel rather than the mild or low-alloy steel. Both the weld metal and the stainless steel have good ductility and can absorb the stress cycles without premature failure. When using the stainless steel or the high-nickel overlay, the joint design must be altered to provide space for the buttering layer.

Welding Steel to Different Steels

Steels that have similar metallurgical structures are normally welded with electrodes matching the composition or behavior of the lower-strength material. This applies not only to various grades or strength levels of carbon and low-alloy steels but also to various grades of stainless steels. For example, a 316 stainless steel should be welded to a 304 stainless steel with a 308 composition filler metal. The 308 would slightly overmatch the 304 composition.

Another example would be the welding of a quenched and tempered steel to a low-alloy high-strength steel. The electrode normally used for joining the low-alloy high-strength steel to itself should be used for welding it to the quenched and tempered steel. The heat input requirements of the quenched and tempered steel should be followed and in all cases a low-hydrogen deposit is required. Another example is the welding of a low-chrome-moly steel to a plain carbon mild steel. In this case, the standard E7018 electrode or filler metal designed for the carbon or low-alloy steel would be used.

Conclusion

When welding dissimilar metals it is important to consider the problem areas. These relate to the solubility of the metals with one another and the formation of brittle alloys. Second, they relate to the difference in thermal expansion and contraction and the recommended use of ductile weld metals to help absorb these stresses. The buttering technique is most often used. Other techniques involve the plating or coating of one of the base materials with a material compatible to both metals and then making the weld. Bimetallic, composite transition inserts, which can be welded to each type of base metal, are used for certain combinations. Information about joining less common metals can be found in Welding Research Bulletin 210.[7]

QUESTIONS

18-1. What property of cast iron makes it difficult to weld? Why?

18-2. Why is a full-penetration weld necessary for repairing cast iron?

18-3. Identify the four types of covered electrodes for cast iron welding. What is the advantage of each?

18-4. Why is preheat usually specified for welding cast iron?

18-5. Tool and die welding is very complex. What are the important factors?

18-6. How are deformed reinforcing bars identified? Why is this important?

18-7. Describe the different types of splices of reinforcing bars.

18-8. Low-hyrogen electrodes are required. What else is required for successfully welding rebars?

18-9. What safety precaution should be taken when welding galvanized steel?

18-10. Why is the galvanized coating damaged adjacent to the weld?

18-11. Why is GTAW not recommended for welding galvanized steel? How can the difficulty be reduced?

18-12. How can the galvanized coating be repaired alongside the weld?

18-13. What welding technique should be utilized when welding free-machining steel?

18-14. Why shouldn't preheat be used when welding Hadfield manganese steel?

18-15. When welding clad metals which side should have the V groove? Why?

18-16. Which side should be welded first, the clad side or the steel side?

18-17. When making a T joint of clad metal, should alloy or steel electrode be used?

18-18. What makes welding different types of metal together more difficult? Why?

18-19. What is a transition piece? Where is it placed in the joint?

18-20. What welding processes are used to produce transition pieces?

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19

Design for Welding

OUTLINE

19-1 WHY WELDED CONSTRUCTION?

A weldment is an assembly whose component parts are joined by welding. A weldment can be an all-welded ship, a skyscraper, an automobile body, a bicycle frame, or a coffee pot, but in any case it must be designed as a weldment. The weldment must meet its service life performance requirements at a minimum cost and have a pleasing appearance. To do this, it should be designed initially as a weldment and not designed as a riveted structure or as a casting or forging and then switched. To properly utilize the tremendous cost savings potential of welding, the structure or part must be designed as a weldment from the beginning. Too often designers remembering the principles learned for riveted or bolted design may use lap type joints in weldments, or the designer remembering the principles of casting design may incorporate thicker sections than are required for the strength of the part. The weldment must be designed strictly to satisfy the functional requirements of the part.

Designers of welded parts and structures must design weldments to perform the required function with the least amount of material and the minimum amount of production labor. This requires some ingenuity, but the results obtained from intelligently utilizing the advantages of weld design are worth this effort.

The most economical solution to a design requirement will be accomplished if the designer intelligently takes into consideration these ten points.

1. The total service requirements of the product
2. The types of loadings and methods of accurately calculating stresses
3. The allowable working stresses
4. The mechanical and physical properties of base materials to be used
5. The capabilities of the welding processes to be used and the weld deposit properties
6. Joint types and weld types—their design and limitations
7. Fabrication methods available—the advantages and potential problems and costs
8. The cost of welding when using different processes and procedures
9. Clear-cut communications of weld designs including the use of welding symbols
10. Quality specifications and inspection techniques

Weldments offer many advantages over other design concepts.

1. The weldment is normally lighter in weight than cast or mechanically fastened structures; thus it requires less material.
2. The weldment design can be readily and economically modified to meet changing product requirements.
3. The production time for a weldment is usually less than that of other manufacturing methods. (This is a hidden cost savings benefit.)
4. The weldment will be more accurate with respect to dimensional tolerances than a casting (another hidden cost savings advantage).
5. Weldments are more easily machined than castings.
6. Weldments are tight and leakproof and will not shift or give like riveted structures.
7. The capital investment for producing weldments is much lower than that for producing castings. Additionally, environmental controls are more easily adopted to the welding shop than to the foundry.
8. Weldments can be more pleasing to the eye than castings. They are cleaner in their lines and usually smoother and more easily prepared for final use.

The two examples mentioned in the beginning of this book should be reexamined. Compare the welded and riveted splice and prove to yourself the reduction in material and in production labor. There is the advantage of splicing pipe by means of welds versus mechanical methods. This will allow the entire system to be made of thinner wall pipe with a great savings in the cost of the pipe. It also provides a smoother surface for the material traveling through the pipe. Also consider the advantage of welding when different types and strengths of metals can be placed strategically within the weldment to meet design requirements.

Note the savings obtained with the welded truck brake shoe when compared to the cast design (Figure 19-1). The weight of the rough casting is 23 lb (10.5 kg) and the weldment is 13 lb (5.8 kg). The extra material and machine work penalize most casting designs. Quantity production is required to justify the blanking dies for the web plates and also for the two welding operations. This is a good example of tooling for high-volume production of a weldment.[1]

Normally, the weldment is less expensive than the casting or mechanically assembled structure. Whenever this is not true it is an indication that the weldment design is less than optimum or there is some other factor or circumstance involved.

Ultimately, the success or lack of success of a weldment lies with the designer. The designer is responsible for the design of the weldment and it is essential that the designer be fully aware of these responsibilities. All of the following comments concerning weldment design are for products made of carbon steel or low-alloy steels, which are most often used for making weldments. The principles involved apply for other metals.

The designer must have a clear understanding of the service requirements and expected service life of the product being designed. It is the designer's responsibility for developing a product that will properly function under the service conditions that it will encounter. In addition, the designer must be completely aware of the properties of the materials involved and how the materials must be treated and handled in fabricating and welding. The design, the materials to be used, and the production

FIGURE 19-1 Welded and cast truck brake shoe.

procedures are interrelated and must be considered when making the design. Design factors are sometimes covered by specifications or codes. In a sense, the specifications relieve the designer of some of these responsibilities, specifically with respect to working stresses, minimum weld sizes, and so on. However, even with codes and specifications the interrelationships of materials and manufacturing methods must still be considered.

Design of weldments can be extremely difficult because weldments cover such a wide variety of parts ranging from miniature pieces in precision equipment through heavy massive machinery. Weldments are used to build transportation equipment such as railroad cars, locomotives, truck frames, airplane frames, automobiles, and ships. Weldments become storage tanks, pressure vessels, and missile cases. Weldments also become simple single-span bridges and complicated structures such as offshore drill rigs, ore unloaders, giant stripping power shovels, and the tallest building in the world. It is difficult to provide detailed information for each of these types of weldments, and therefore only general comments will be made concerning design systems and design concepts. It is the designer's added responsibility to select and choose the correct weld configurations to properly carry the loads to sustain the service life of each weldment designed. It is fundamental that the designer give attention to the following principles:

The economic factors must be considered. The first costs of the weldment may not always be the determining factor. Maintenance and repair cost over the life of the weldment may be more important than the initial cost. The initial cost must be considered concurrently with economic benefits to be derived from welded construction.

Weight reduction is desirable for moving structures such as railroad rolling stock, construction equipment, highway trucks, and so on. Increased payloads and reduced energy required to move such structures plus cost of materials makes a strong case for designing to minimum weight. Welding allows for weight reduction by utilizing the full section of members.

Utilization of high-strength metals becomes increasingly important in reducing weight and cost. The designer must select the strength level and the strength–density relationship of the metal to be used in the weldment.

Dynamic loading is most common in moving equipment. This factor has an effect on the fatigue life of the structure. It is based on reversal of loading but is also involved with varying loads either tensile or compression. Impact loadings can increase the normal static stress by factors as high as tenfold. This has a great effect on weldment design.

In conjunction with dynamic and impact loading, the service temperature is important. Structures exposed to extreme low temperatures, like those encountered with construction equipment operating in the arctic, and severe dynamic loads, must be very carefully designed to sustain these loads. Cold temperatures magnify the problems of stress concentrations and design notches, and make notch toughness more important.

In some cases, the loading of the weldment is strictly of a static nature and no movement is involved. Under these conditions fatigue loading or impact loading can be ignored.

In some weldments, corrosion resistance might be a major factor with respect to service life. Corrosion exposure largely determines the metal that will be used for the weldment and also is a major factor in the selection of the welding process and procedure.

There are other problems such as exposure to high temperatures that may be continuous or intermittent. Continuous high temperature poses a design problem but temperature changes can be more difficult for the designer. Coupling high temperatures or intermittent high and low temperatures with corrosive atmospheres compounds the designer's problems.

Another important factor is resistance to the abrasion that can occur from use in construction equipment or the interacting of moving parts. Special metals can be placed at wear points. There are many other service related factors that should be considered, such as exposure to nuclear radiation, exposure to potential vandalism, plus exposure to a combination of many of the factors mentioned previously.

The designer must have a clear-cut understanding of the fabrication procedures and techniques that will be involved in the production of the weldment. This would include such factors as the ability to oxygen flame cut, shear, or machine the material. The designer must also know whether it is possible to form the material cold or whether hot forming is required. The designer must know if the metals can be welded and if special precautions are required. The weldability of the material to be used for the product is of utmost importance in the design of any weldment.

The designer must provide the inspector with guidance to select the class of inspection required and indicate special requirements for specific weld joints. The type of nondestructive testing should be specified and tolerances for dimensions should be given.

Finally, the designer must transmit to the welding shop the exact specification for each weld by means of welding symbols. At the last, or perhaps it should be first, the designer must make sure that every weld joint is accessible to the welder and can be made.

19-2 WELDMENT DESIGN FACTORS

The design of a weldment involves the efficient and economical use of metals. It also involves the design of all weld joints used to make the weldment. We have previ-

ously mentioned the service conditions to which the weldment will be exposed and have covered the factors that the designer must consider in designing the weldment to meet these service requirements. In order to satisfy the service requirements the designer must have reliable information of the performance characteristics of the metals that are used. Most designs are based on an analysis of the stresses imposed on the part or structure. The designer must completely and accurately determine the loads that will be encountered. The **load** is the force that stresses a part.

It is beyond the scope of this book to develop how loads imposed on structures are calculated and how these loads develop specific stresses within the part. Since we are concerned with the welding phase or the design of the welds rather than the total design of the part, no extended treatment of stress analysis will be given. There are many excellent handbooks on machine design and structural design. It is important to point out that the more accurately these loads and stresses can be determined the more efficient the design of the weldment will be.

Stress analysis must include static loadings, and dynamic loads, including impact and fatigue that are involved. The structure must support its own weight, the dead loads, and the superimposed loads and forces produced by all service conditions, including all live loads and forces, centrifugal or accelerating and decelerating action, transmission of loads, erection loads, loads due to thermal stresses, and so on. The term *load* is used here in an all-inclusive sense to cover all the external forces acting on the weldment that cause internal stresses.

In the design of a weldment it is necessary to establish the outlines of the proposed part or structure and then to determine all the different loads and forces and environmental conditions that will be imposed upon it.

The weldment must be designed to resist these imposed forces and this depends upon the mechanical and physical properties of the metal that become the weldment. The important properties of the base metals are the yield strength, the ultimate strength, and the modulus of elasticity. The allowable working stress must be determined, the factor of safety of the weldment must be established, and the cross-sectional area of the parts can then be calculated.

The *allowable working stress*, sometimes called allowable unit stress, is the maximum stress level that is allowed anywhere within the weldment. The stresses within the weldment, calculated by the various formulas based on the type of loading, must not exceed this value. The allowable working stress may be dictated by a code or specification. Different values are given for different materials or different grades of steels and for different kinds of loadings. Handbooks provide this information. When a code or specification does not apply, the allowable working or unit stress is calculated by dividing the yield strength of the material by a factor so that the part would not be subjected to stresses above its yield point. If this were to happen, the part would deform and possibly fail. This factor is known as the *factor of safety*.

The factor of safety has an extremely important bearing on the economics of a design. In order to produce the lightest-weight weldment utilizing the least amount of material the factor of safety should be the lowest. For example, in the design of missile cases, the factor of safety may be as low as 1.25. The selection of the factor of safety must be based on several factors, and the accuracy with which loads are selected to represent service conditions has a great bearing. When these loads can be determined with great accuracy, the factor of safety can be lower. If there is doubt or there are numerous assumptions about the loads, the allowable working stress should be more conservative or lower which makes the safety factor higher. Approximations are often used in determining loads on members and their accuracy is based on the designer's experience. However, with accurate experimental work to determine loads the expected service life can be attained with a lower factor of safety. Finally, it is important for the designer to consider thoroughly the importance of the structure or weldment and the possibility of damage that might occur if it were to fail. The factor of safety used in designing many weldments is based on experience from previous application of weldments in similar service situations. In general, it is possible to reduce the factor of safety when a strict quality control program is utilized to insure that the materials and welds are precisely designed. In most structural work and machine design, a factor of safety of 1.8 is commonly used. However, it is the responsibility of the designer to select the proper factor of safety and allowable stresses for materials utilized, based on the service requirements.

The internal forces normally called stresses that occur within the structure can then be calculated. In simple tension this would be done by dividing the load or force by the cross-sectional area of the component that resists these forces. Dividing the force by the cross-sectional area of the part will determine the unit stress. The cross-sectional area is proportioned to provide sufficient area so that the internal stress does not exceed the allowable working stress for the type of loading and the metal used in the weldment. There are special cases such as long, slender columns, in which the length to slenderness ratio is the controlling factor since such members may fail by buckling. Bending loads also need special analysis.

For the designer to better analyze the stresses in a weldment it is common practice to classify the types of loads that are imposed and from these to determine the types of stresses in the structure. The five basic types of loads on a weldment are as follows:

1. Tensile load

2a. Compression-load (short section)
2b. Compression-load (long section)
3. Bending loads
4. Torsion load
5. Shear load

Most all loadings can be categorized as one of these. In many cases it is necessary to consider combinations of these loads. It must be remembered in considering loads and stresses in a weldment that the weldment is a monolithic structure and that all pieces work together. In other words, a load imposed on one particular piece of a weldment is transmitted through the weld joints to the other pieces of the weldment. For simplicity's sake, it is usually assumed that the parts are connected by welds and that the weld transmits the load from one part to another.

Most design work is classified as either structural design or machine design. In general, structural design refers to large structures usually made of hot rolled steel sections such as angles, bars, plates, beams, etc., connected at intersecting points by welds. Machine design on the other hand normally involves smaller, more compact weldments made of parts cut from steel plates and sometimes castings welded together at all interfacing points. As an example, compare a roof truss which is a structural assembly to a machine tool base, which is made of steel plates. The design analysis techniques are different for these two types of weldments.

A *tensile* load is the simplest type of load. The axial load is indicated by the letter F, indicating force or tensile force. The load, parallel to the axis, is divided by the cross-sectional area, A, which is the product of the thickness t, and width l, to give the unit stress indicated by S. Thus the equation

$$S = \frac{F}{A} \quad \text{or} \quad \frac{F}{tl}$$

Such stresses and loading are considered to be uniform over the entire cross-sectional area. The cross-sectional area can be taken anywhere along the member or through the throat of the butt weld joint. In normal weldment calculations the weld reinforcement is ignored and a unit stress is based on the theoretical thickness by the length of the weld (Figure 19-2).

A *compression* load is the opposite of a tensile load if it is imposed on a short member. Figure 19-3 illustrates this situation with the loading and equation identical to that of the tensile load; however, in this case the load results in compression of the weld. In most metals the mechanical properties in compression are not as clearly defined as those in tension. There is no definite ultimate strength, although there is a yield point which is generally considered to be equal to the tension yield point. Beyond this yield point there is plastic flow and lateral expansion of ductile metals. For short compression members the basic working stress in compression is assumed to be equal to the working unit stress in tension. Hence the same formula applies except that the load is compressive rather than tension.

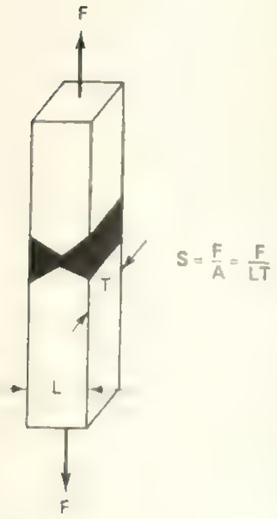


FIGURE 19-2 Tension loading.

The *compression load* on long members requires a different analysis. As the length of a member increases, failure takes place by buckling at an average compressive unit stress less than the yield point. By definition a column is a straight member subjected to compressive forces acting in the direction of its axis (Figure 19-4). If the length of the column is sufficiently great compared to its cross section, failure will take place by lateral bending or buckling. Unlike tension and short-compression members, the fiber stress in columns is not directly proportional to the load. Loading of columns is a technical subject too complex to be treated here. If the loading on the column becomes eccentric or not exactly on the axis of the column the tendency to buckle increases. Long slender members subjected to axially compressive loads should be designed with utmost caution. Flat plates can

FIGURE 19-3 Compression loading.

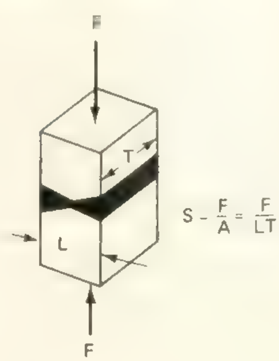


FIGURE 19-4 **Compression loading: long member.**

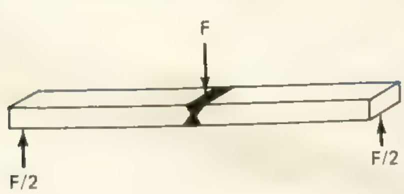
also be exposed to compressive loads on the edge. In such cases, local buckling will occur in short lengths of a section due to its elastic instability under the action of a compressive load. The buckling of a flat plate of a ductile material does not necessarily mean failure of the entire member since it may occur while the member is still capable of carrying additional load.

Bending is a common type of loading, both in structural and machinery applications. Many machine and structural parts act as beams and their primary function is to support various loads. These loads tend to produce bending in the part (Figure 19-5). Internal stresses due to bending are of two types: one called *fiber stresses* (also known as normal or bending stresses), which act perpendicular to a transverse cross section of the beam, and the other called *shearing stresses*, which act in both the transverse and longitudinal directions.

Maximum fiber stress in a beam occurs at the fibers farthest from the neutral axis. For beams with a symmetrical cross section about the neutral axis, the section modulus to either the top or bottom extreme fibers is the same. For beams with an unsymmetrical cross section the section modulus to each extreme fiber is different. The fiber stress resulting from bending is given by the formula

$$s = \frac{M}{S}$$

FIGURE 19-5 **Bending loading.**



where s = fiber stress
M = external bending moment
S = section modulus of the beam under consideration

Most handbooks on design provide values of the section modulus (S) for rolled structural steel shapes and commonly used built up sections. The section modulus can also be expressed as I divided by c, where I is the moment of inertia of the section of the beam about its neutral axis and c is the distance from the neutral axis to the extreme fiber. The basic allowable unit stress for extreme fibers tension due to bending is the same as that allowed in simple tension.

The shearing stress at any point in a beam is given by the formula

$$v = \frac{V}{dt}$$

where v = Shearing stress
V = vertical shear load
d = depth of the beam
t = thickness of the web or vertical portion of the beam

Normally, the shearing stress in bending is a maximum at the neutral axis and zero at the extreme fibers.

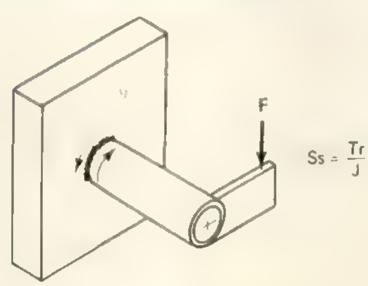
There are many different types of loading of beams and there are many different support systems for beams.

Torsion, the next type of loading, is based on forces attempting to twist and forces resisting. The internal stress that results from these two twisting forces is actually a shear stress. This is shown in Figure 19-6, in which a twisting motion is attempting to shear the weld joining the rod to the plate. The equation for torsion is

$$S_s = T \times \frac{r}{J}$$

where S_s = shear stress
T = torque expressed in force multiplied by distance from the centerline of the axis of the part being twisted
r = radius of the tube being twisted
J = polar moment of inertia of the circular part being twisted

FIGURE 19-6 **Torsion loading.**



The polar moment of inertia is available in design handbooks for round members. In the case of the weld shown in Figure 19-6, the polar moment of inertia of the failure area or throat of the fillet weld would have to be calculated. This formula should only be used for circular cross-sectional areas subjected to torsion. Formulas for other cross sections subject to twisting loads are very involved and must be individually calculated.

Shearing stress is the force acting in the plane of the cross section. This is in contrast to tensile and compressive stresses which act perpendicular to the plane of the cross section of a member. The failure area in shear is parallel to the load and the stress is caused by two equal and opposite parallel loads. It can be thought of as the load attempting to slide two pieces apart. The equation in this case is

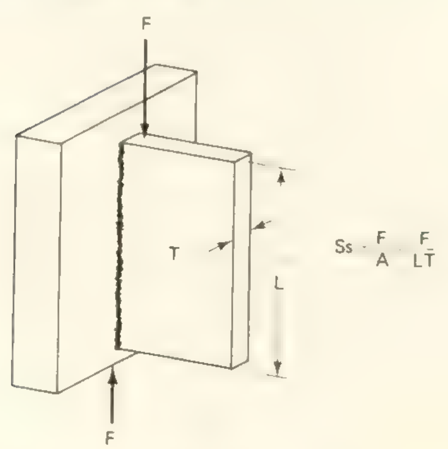
$$s = \frac{F}{A}$$

where s = shear stress
F = force
A = area, but as mentioned above, it is an area parallel to the loads

It is common practice to assume that the weld is stressed equally over its entire area, although this is not precisely true. The shear is shown in Figure 19-7. Shear is extremely important with respect to welding. Fillet welds fail through the throat, which is considered a shear failure. The controlling stress in a fillet weld is shear instead of tension or compression. Failure usually occurs by shear at 45° along or through the throat section.

Fillet welds are the most widely used welds. Since it is somewhat controversial to compare longitudinally versus transversely stressed fillets it is interesting to review Figure 19-8. This figure shows that the shear stress is identical in either situation providing that bending does not occur. The stress distribution is more uniform in the transverse weld than in the longitudinal fillet, which is parallel to the line of force. This type of connection is widely used for the welding of structural angles to plates. The different types of loading and the stresses that result can act singly but in many weldments they may act in combination. Combined stresses should be given special attention. These are defined as stresses acting simultaneously at a point in more than one principal direction. Under combined stresses, in steel and other ductile metals, yielding may occur at a stress that is less than the *uniaxial* (stress in one direction only) yield stress. Combined stress will more often occur in extremely thick sections.

FIGURE 19-7 Shear loading.



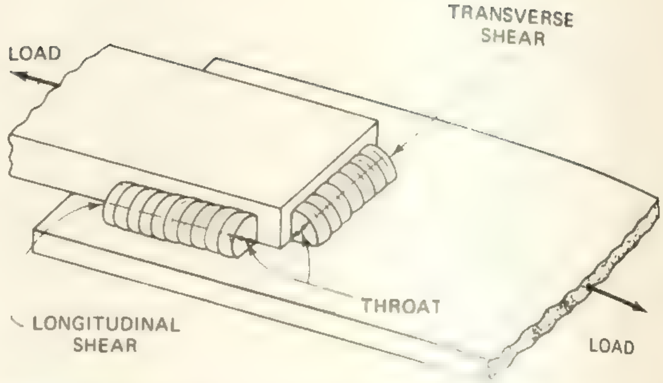


FIGURE 19-8 Stresses in a fillet weld

The foregoing information should give you an idea of the calculations necessary to determine stress in sections based on applied loads. It is not intended to cover complex loadings of machine parts or structural members. The designer should consult a design handbook for additional information concerning calculation of stresses based on different types of loading.

Stress Concentrations

When considering the design criteria of a weldment special emphasis must be placed on stress concentrations or the distribution of stress at notches or discontinuities. When the parts of a weldment are welded together they all act as a monolithic structure. This means that stresses are spread throughout the entire structure when transmitting a force from one point to another within the structure. Designers may claim that a particular part is not expected to carry any of the load. However, once that piece is welded to the total weldment it becomes a part of the weldment and will carry a portion of the load. Tensile stresses are normally thought to be uniformly distributed throughout the entire cross section of a member. This is usually a safe assumption for simple statically loaded structures. However, complex structures exposed to static dynamic loading, repetitive loading, and impact loading will not have a uniform stress pattern across the structure. The effect of the nonuniformity is more important in fatigue and cold weather impact.

Under some service requirements external loads may fluctuate or may be applied *repetitively* thousands of times. Most metals exhibit a lower ultimate strength under the application of repetitive loads and it is normal practice to reduce the working unit stress when cyclic or repeated loading is applied. This involves the fatigue life of the metal and depends upon the stress cycle imposed. The types of stress cycle refer to whether there is a complete reversal of stress from tension to compression or whether it is a loading from a minimum to a maximum amount of either tension or compression. Most codes specify an allowable fatigue stress.

Suddenly applied loads are called *impact loads* and the suddenness of the application of the load is a matter of degree of the impact. The effect of impact is to immediately increase the internal stress in the weldment. These internal stresses may be localized and cause problems. In a weldment the stresses remote from the point of application of the load will be considerably less than at the point of loading. The design calculations are made on the basis of equivalent static load conditions. It is normal practice to allow for the effect of impact-producing stresses by the use of factors based on static loading. An alternative is complete calculation of the stresses. The factor is an across-the-board cut in the allowable unit stress of the total structure or weldment.

A stress concentration is a point within the structure at which the stresses will be more concentrated than throughout the remaining cross-sectional area of the weldment. Stresses at a notch, for example, can be two to four times as great as the stresses throughout the remaining portion of the structure. This may not be harmful to the statically loaded weldment but to weldments loaded dynamically, repetitively, or by impact, it can create a point of premature failure. A simple example of a stress concentration based on the presence of a notch is shown in Figure 19-9. On the left the bar stressed in tension will have uniform stress throughout its cross section. The bar on the right has a sharp notch in the edge and the stresses will be concentrated at the root of the notch. Even though the stresses were uniformly distributed at the ends of the bar, they cannot be transmitted through the notch; therefore, they are concentrated at the root of the notch. The bar with the notch will have service life considerably less than the bar not containing the notch.

There are three basic types of notches that result in stress concentration. They are:

1. Design notches both in weldments and in welds
2. Workmanship notches of weldments but more importantly of welds
3. Metallurgical notches

A design notch is designed into a weldment, such as in an abrupt change of section. A practical example is a square hatch opening in the deck of a ship. The section at the point where the hatch opening occurs changes abruptly and there is a concentration of stresses. Another similar design notch would be the attachment of a deckhouse welded to the deck of a ship. The section changes drastically at the point the deckhouse is welded to the deck. It might be argued that the deckhouse is not expected to carry any of the load or stress. It will, since it is welded and becomes integral to the other parts of the hull. The intersection of members, re-entrant angles, abrupt reinforcing structures, and square holes are all examples of notches in the design of weldments.

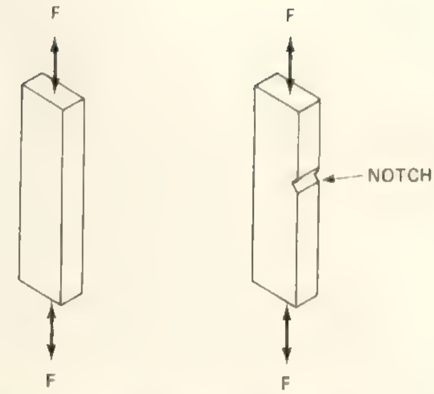
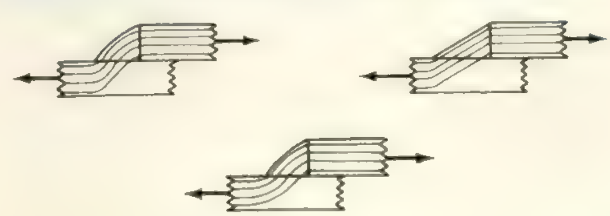


FIGURE 19-9 Bar with and without notch.

Notches also occur in welds.[2] A design notch in a weld joint would be the incomplete fusion area at the center or root of a weld. Any weld joint design which provides partial penetration or incomplete fusion includes a notch. Fillet welds used for lap joints are notch prone. See Figure 19-10 for examples of stress concentration when the joint is loaded in tension. T joints made with fillets are also notch prone. The worst notch is the single fillet welded T joint. Figure 19-11 shows these T weld joint details and how different designs contain notches. This figure shows three joint designs, the stress paths, and a comparison of their relative static tensile strength, resistance to fatigue, and impact strength. The static strength is determined by the area of the weld, the other factors by tests. Butt joints are less notch prone because of their geometry. Full-penetration welds produce highly efficient butt joints. However, partial penetration welds contain notches at the center of the weld or at the outer surface. Four examples are shown by Figure 19-12. It is

FIGURE 19-10 Single fillet lap weld in tension.



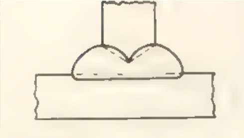
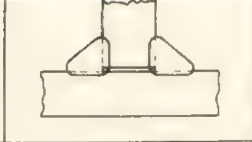
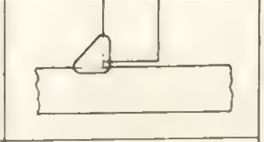
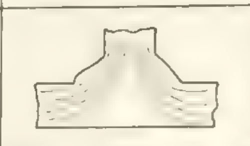
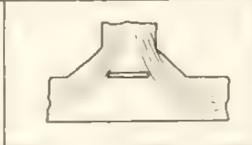
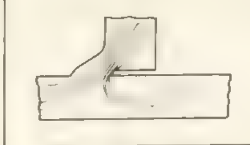
Tee Joint with groove and/or fillet welds			
Stress pattern			
Static tensile strength	100%	80%	30%
Resistance to fatigue	40%	25%	10%
Impact strength	85%	75%	10%

FIGURE 19-11 T joints: stress pattern.

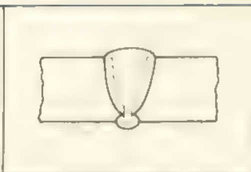
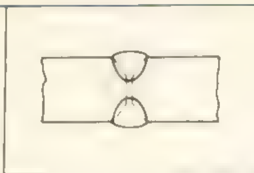
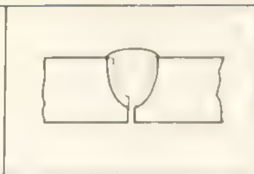
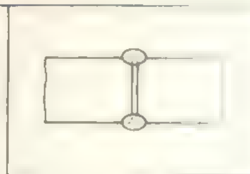
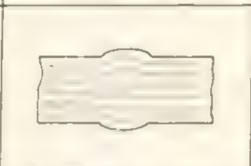
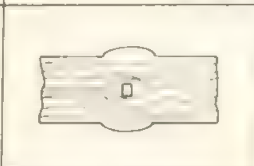
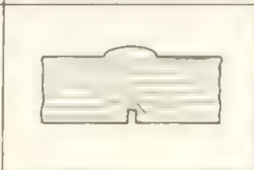
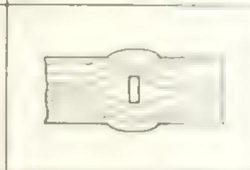
Butt joint with groove welds				
Stress pattern				
Static tensile strength	100%	85%	70%	60%
Resistance to fatigue	100%	35%	15%	10%
Impact strength	100%	80%	65%	40%

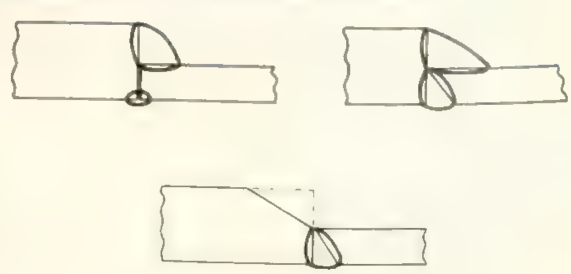
FIGURE 19-12 Butt joints: stress pattern.

easy to determine whether a notch is designed into the joint by drawing a cross section of the weld joint indicating the paths that the lines of stress must follow. Notches can also occur in weld joints when the section changes abruptly. Figure 19-13 shows three butt joints between a thick and a thin member. There are several ways to provide a smooth stress flow through the weld. There is also a way to make two stress concentrations. The left joint in Figure 19-13 would create two points of stress concentration, one at the toe of the fillet and one at the unfused root. The right joint would be a better solution and would provide a relatively smooth stress flow. The joint on the bottom would also provide a relatively smooth stress flow and would be less expensive since less weld metal is required.

Workmanship notches can be troublesome and difficult to control. These occur when the welds are not full-penetration welds, even though they are designed to be. The root opening may have been eliminated by an accumulation of tolerances, or back gouging and rewelding may have been omitted. A fillet weld at the point of joining a thin section to a thick section may not be full size and will create a notch.

The third notch factor is in the minority and creates the least trouble. These are metallurgical notches which may be caused by joining metals of different yield strengths, or by welding on hardenable steels and creat-

FIGURE 19-13 Thick to thin butt joint.



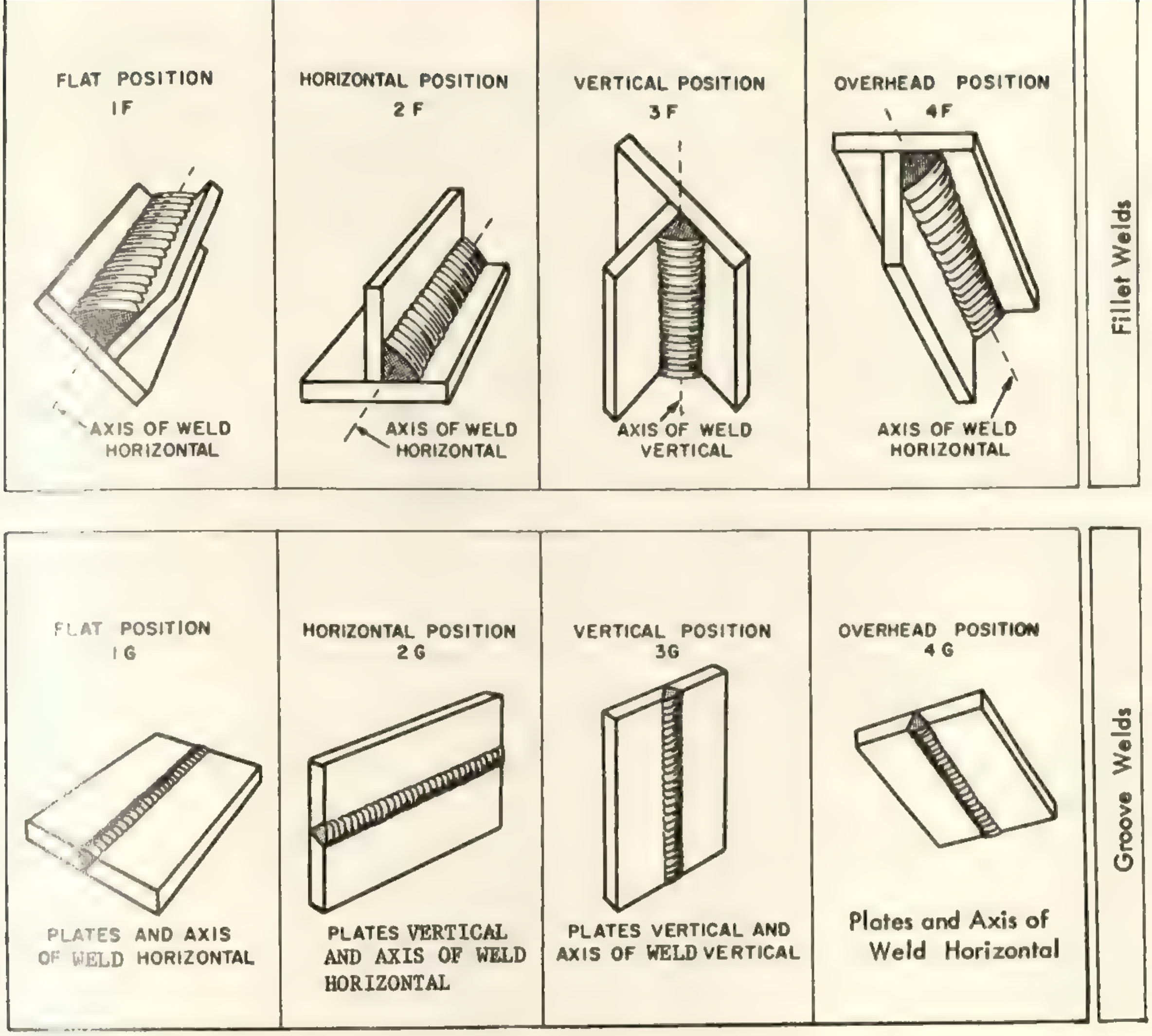


FIGURE 19-14 Welding positions for fillet and groove welds.

ing extremely hard spots in welds. Abrupt change in strength along a cross section can have the effect of a notch even though there is no abrupt change in section.

In the design and construction of weldments subjected to dynamic loads and low-temperature service, every effort must be taken to provide a smooth flow of stress lines throughout the weldment. This becomes more important when high-strength materials are used.

Rigid Frame Construction

This type of construction, also called continuous construction, is a design system incorporating *plastic analysis*. This type of design and construction is specifically suited to welded construction. In this type of work the members are welded directly together rather than through connection plates, gussets, or filler plates. The material in a rigid or continuous welded frame is utilized more efficiently because the bending moments are distributed better. This type of construction provides the maximum degree of end restraint. Rigid frame design allows large savings in steel of the members involved. It also eliminates the steel of the connecting plates, gussets, and so on. It requires a more thorough analysis and should be done only by designers well qualified to perform this type of work.

In machine members the rigid connection concepts or plastic analysis provides for greater dimensional accuracy. The weldment will maintain correct alignment and dimensional accuracy throughout its service life. This type of design and construction should be used for all welded machine parts, unless they must be disassembled.

19-3 WELDING POSITIONS, JOINTS, WELDS, AND WELD JOINTS

Welding Positions

Often, welding must be done on the ceiling, in the corner, or on the floor. Welding must be done in the position in which the part will be used. We must be able to describe and define these different welding positions. The American Welding Society has defined the four basic welding positions as follows (Figure 19-14):

- *Flat:* the welding position used to weld from the upper side of the joint; the face of the weld is approximately horizontal.
- *Horizontal:* the position in which welding is performed on the upper side of an approximately horizontal surface and against an approximately vertical surface. For pipe welding, the weld axis lies in an approximately horizontal plane and the weld face lies in an approximately vertical plane.
- *Overhead:* the position in which welding is performed from the underside of the joint.
- *Vertical:* the position of welding in which the weld axis is approximately vertical.

There are at least two foreign definitions that are different from those of the American Welding Society. The British and others use the term *downhand* to describe the flat position. This term is quite descriptive and is also used in the United States. They also use the term *horizontal-vertical* to describe welds between plates, one in approximately the horizontal plane and one in the vertical plane when the axis of the weld is approximately horizontal. The positions are identified as follows: F indicates fillets, 1 indicates flat, 2 indicates horizontal, 3 indicates vertical, and 4 indicates overhead. The same numbers apply to groove welds, which are designated with the letter G.

Pipe weld joints are a special case and are identified as test positions (Figure 19-15). They are normally groove welds and they are indicated by the letter G. Test position 1G is roll welding with the axis of pipe horizontal, but with the welding done in flat position with the pipe rotating under the arc. Test position 2G is known as horizontal welding but the axis of the pipe is in the vertical position with the axis of the weld in the horizontal position. There is no 3G or 4G test position on pipe welding. Test position 5G is known as horizontal fixed position. Here the axis of the pipe is horizontal, but the pipe is not to be turned or rolled during the welding operation.

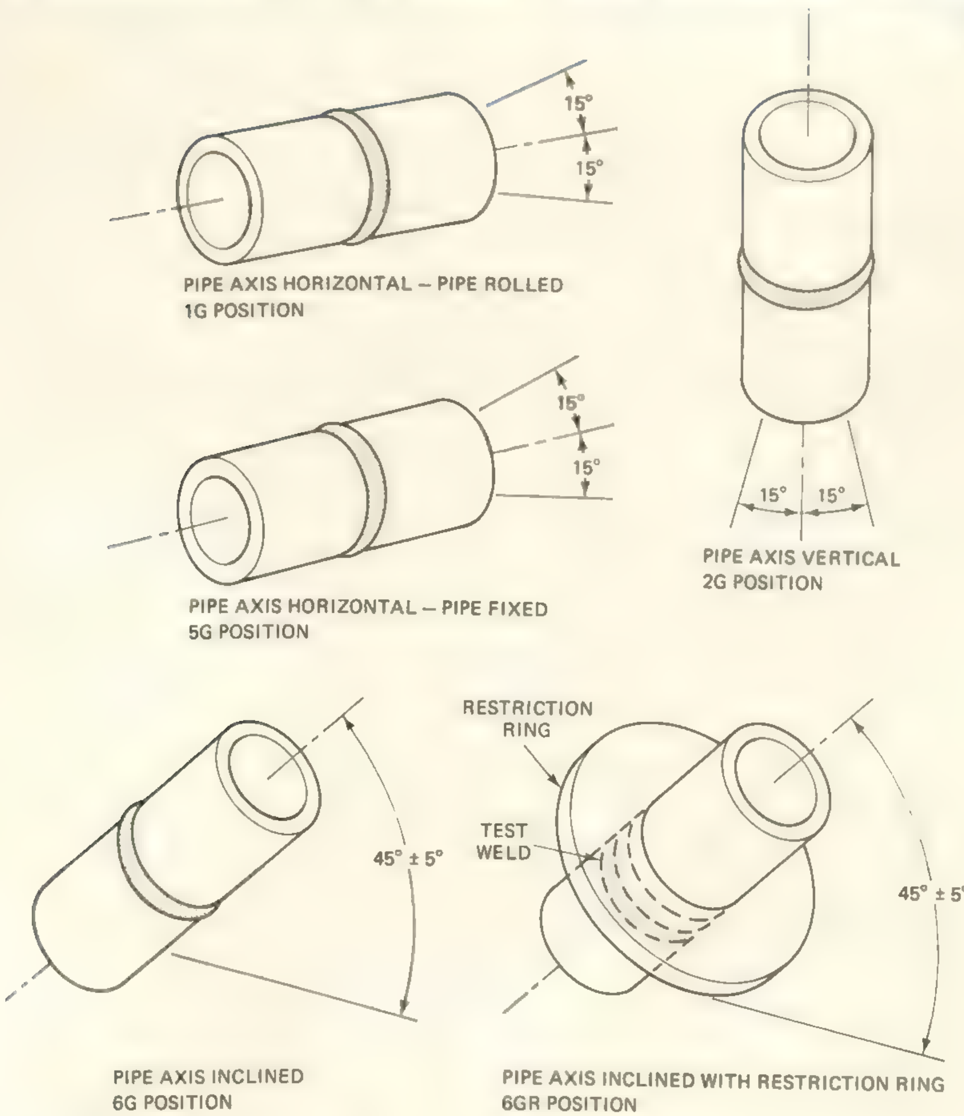
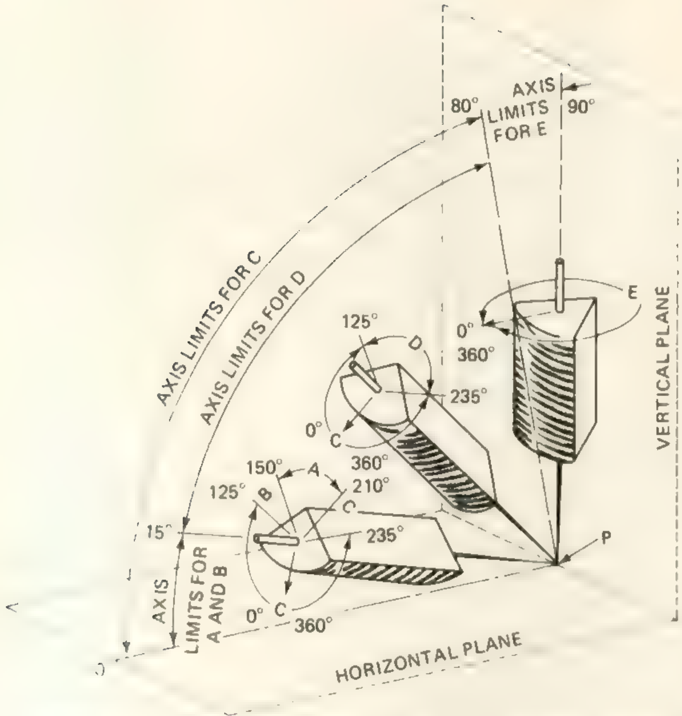


FIGURE 19-15 Welding positions for pipe welds.



TABULATION OF POSITIONS OF FILLET WELDS			
POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	125° TO 150°
			210° TO 235°
OVERHEAD	C	0° TO 80°	0° TO 125°
			235° TO 360°
VERTICAL	D	15° TO 80°	125° TO 235°
	E	80° TO 90°	0° TO 360°

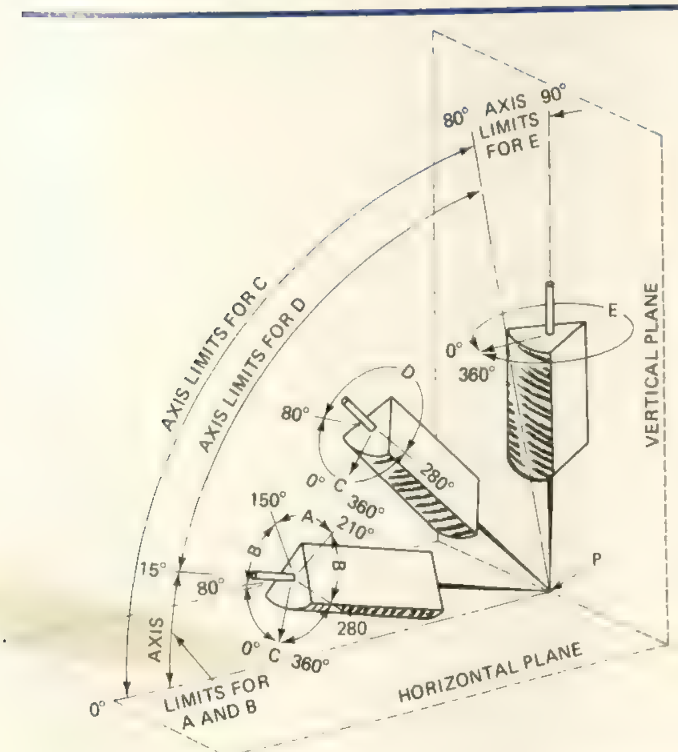
FIGURE 19-16 Welding positions for fillet welds.

Test position 6G for pipe has the axis of the pipe at 45° and the pipe is not to be turned while welding. For qualification work a 6G restricted position is often used. Restricted accessibility is provided by a restriction ring placed near the weld. It is called 6GR. The axis of the pipe may vary ±15° for 1G, 2G, and 5G test positions, but only ±5° for the 6G position. Square and rectangular tubing is accommodated in the 2G and 5G test positions.

The official AWS diagrams for welding positions are precise. They utilize the angle of the axis of the weld which is "a line through the length of the weld perpendicular to the cross section at its center of gravity." Figure 19-16 shows the fillet weld and the limits of the various positions. It is necessary to consider the inclination of the axis of the weld as well as the rotation of the face of the fillet weld.

Figure 19-17 shows the groove weld positions in the same manner. The inclination of the axis of the groove and fillet weld is the same as far as limits are concerned. For the flat position the rotation of the face of the weld

FIGURE 19-17 Welding positions for groove welds.



TABULATION OF POSITIONS OF GROOVE WELDS			
POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	80° TO 150°
			210° TO 280°
OVERHEAD	C	0° TO 80°	0° TO 80°
			280° TO 360°
VERTICAL	D	15° TO 80°	80° TO 280°
	E	80° TO 90°	0° TO 360°

is the same for fillet and groove welds. However, the rotation of the face of the horizontal, vertical, and overhead groove welds are different.

The design of a joint is often changed whenever the welding position or type of backing is changed. In general, narrower included angles are used for other than flat-position groove welds. Welds made in the horizontal position usually have a flat face on the bottom member and a beveled face on the upper member. When backing strips are used the root opening is usually wider. Specific joint details for different thicknesses and positions are shown in the next section.

The welding position must always be accurately described. It is an important variable in any welding procedure. It is especially important with respect to training and qualifying welders and must always be given consideration when selecting a welding process.

Joint Types

Welds are made at the junction of the various pieces that make up the weldment. These junctions of parts are called joints defined as "the junction of members or the edges of members which are to be joined or have been joined." Parts being joined to produce the weldment may be in the form of rolled plate, sheet, shapes, pipe, or they may be castings, forgings, or billets. It is the placement of these members that define the joints. There are five basic types of joints for bringing two members together for welding (Figure 19-18):

- *B, Butt joint:* a joint between two members aligned approximately in the same plane.
- *C, Corner joint:* a joint between two members located approximately at right angles to each other
- *E, Edge joint:* a joint between the edges of two or more parallel or nearly parallel members
- *L, Lap joint:* a joint between two overlapping members in parallel planes
- *T, Tee joint:* a joint between two members located approximately at right angles to each other in the form of a T.

When more than two members are brought together other designs may be used, or they may be a combination of the five basic joints. The most popular is the *cross* or *cruciform joint*—"a joint between three members at right angles to each other in the form of a cross." It is actually a double T joint. The joint describes the geometry in cross section of the members to be welded.

A weld is a localized coalescence of metals or nonmetals. It is produced either by heating the materials to the welding temperature, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler metal.

To describe or specify a "weld joint," it is necessary to describe both the joint and the weld. As mentioned, there are five basic types of joints: butt, corner, edge, lap, and tee. There are a fairly large number of different types of welds and variations which are used to join the members to make a weld joint.

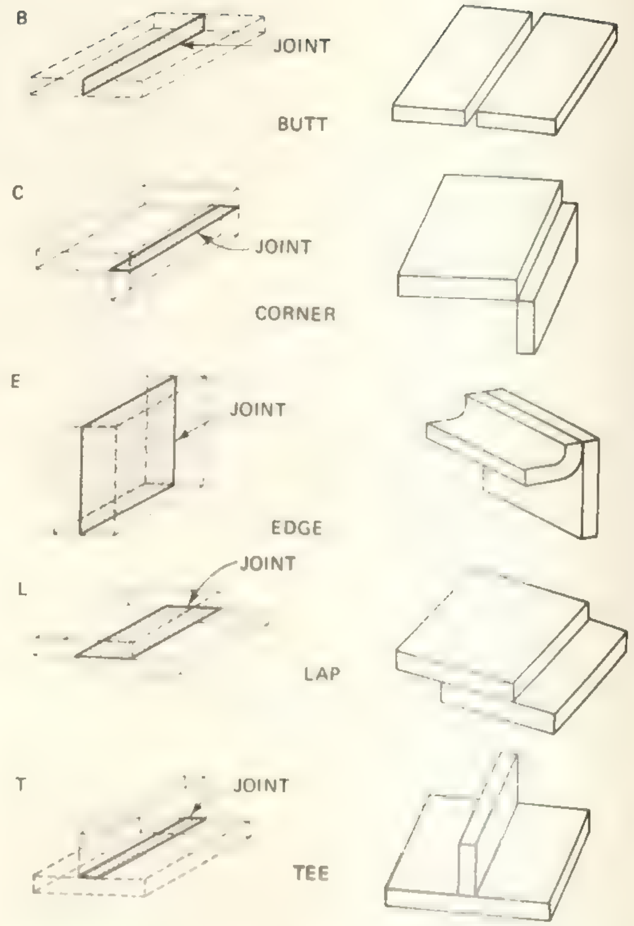


FIGURE 19-18 **Five basic joint types.**

Weld Types

There are a number of different separate and distinct welds, as shown by Figure 19-19. Some of these weld types have many variations. In addition, weld types can be combined. Certain of them such as the fillet weld and groove weld are used for making plate weldments. The different types of welds are:

1. The fillet weld
2. The groove weld—several types
3. The back or backing weld
4. The plug or slot weld
5. The spot or projection weld
6. The seam weld
7. Melt-through weld
8. The flange weld
9. The stud weld
10. The surfacing weld

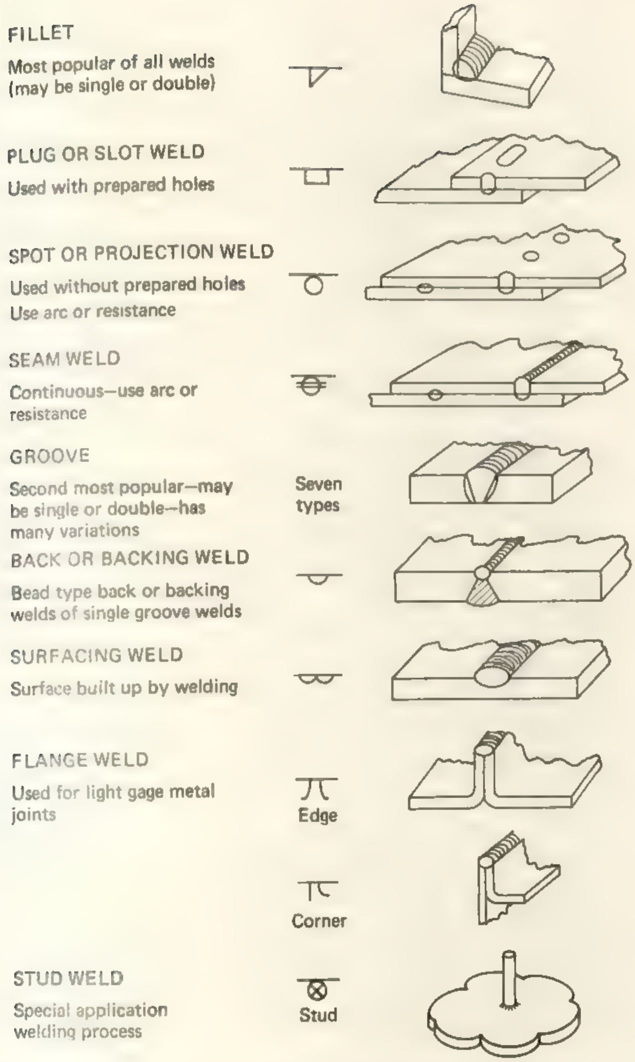


FIGURE 19-19 **Eight basic types of welds.**

Fillet Weld This is the most commonly used weld. The fillet weld is so named because of its cross-sectional shape. The fillet is regarded as being *on the joint* and is defined as "a weld of approximately triangular cross section joining two surfaces approximately at right angles to each other." Details of the fillet weld are shown in Figure 19-20.

Plug or Slot Welds These are used with prepared holes. They are considered together since the welding symbol to specify them is the same. The important difference is the type of hole in the prepared member being joined. If the hole is round, it is considered a plug weld; if it is elongated, it is considered a slot weld.

Spot and Projection Weld This is shown by the same weld symbol. These types of welds can be applied by different welding processes which change the actual weld. For example, when the resistance welding process is used, the weld is at the interface of the members being joined. If the electron beam, laser, or an arc welding process is used the weld melts through one member into the second member.

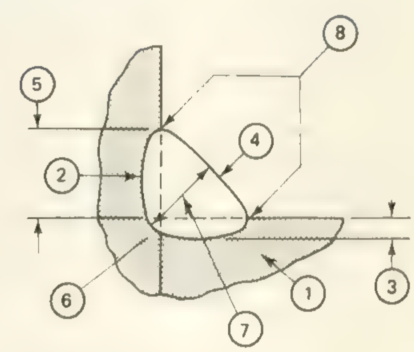
Seam Weld This weld in cross section looks similar to a spot weld. The weld geometry is influenced by the welding process employed. With resistance welding, the weld is at the interface between members being joined, but with an electron beam, laser, or arc welding process, the weld melts through the one member to join it to the second member. There are no prepared holes in either the spot or the seam weld.

Groove Weld This is the second most popular weld type employed. It is defined as "a weld made in the groove between two members to be joined." The groove weld is regarded as being "in the joint." There are seven basic groove weld designs, and they can be used as single or double welds. The details of the groove weld are shown in Figure 19-21.

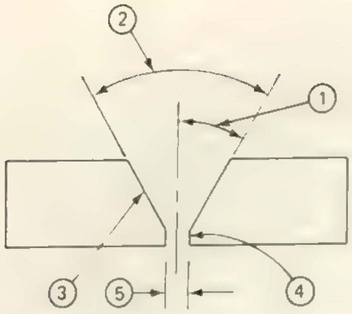
Back or Backing Weld This is a special type of weld made on the back side or root side of a previously made weld. The root of the original weld is gouged, chipped, or ground to sound metal before the back or backing weld is made. This will improve the quality of the weld joint by assuring complete penetration.

Surfacing Weld This is a type of weld composed of one or more stringer or weave beads deposited on base metal

FIGURE 19-20 **Fillet weld.**



(1)	BASE METAL:	Metal to be welded.
(2)	BOND LINE:	The junction of the weld metal and the base metal.
(3)	DEPTH OF FUSION:	The distance that fusion extends into the base metal.
(4)	FACE OF WELD:	The exposed surface of a weld on the side from which the welding was done.
(5)	LEG OF A FILLET WELD:	The distance from the root of the joint to the toe of the fillet weld.
(6)	ROOT OF WELD:	The point or points, as shown in cross-section, at which the bottom of the weld intersects the base metal surface or surfaces.
(7)	THROAT OF FILLET WELD:	The shortest distance from the root of the fillet weld to its face.
(8)	TOE OF A WELD:	The junction between the face of a weld and the base metal.



(1) BEVEL ANGLE: The angle formed between the prepared edge of a member and a plane perpendicular to the surface of the member.

(2) GROOVE ANGLE: The total included angle of the groove between parts to be joined by a groove weld.

(3) GROOVE FACE: The surface of a member included in the groove.

(4) ROOT FACE: That portion of the groove face adjacent to the root of the joint.

(5) ROOT OPENING: The separation between the members to be joined at the root of the joint.

FIGURE 19-21 Groove weld.

as an unbroken surface. It is used to build up surface dimensions, to provide metals of different properties, or to provide protection of the base metal from hostile environment.

Flange Weld Edge This is used primarily for light-gauge or sheet metal joints.

Flange Weld Corner This is also used for light-gauge or sheet metal parts. In both cases, parts must be prepared for these specific joint details.

Weld Joints

In order to produce weldments it is necessary to combine the joint types with the weld types to produce weld joints for joining the separate members. Each weld type cannot always be combined with each joint type to make a weld joint. Figure 19-22 shows the welds applicable to the basic joints. Since fillet welds and groove welds have more possibilities and their use is more complex, more information regarding their use on different joints will be given in the next section.

19-4 WELD JOINT DESIGN

The purpose of the weld joint is to transfer the stresses between the members and throughout the weldment. Forces and loads are introduced at different points and are transmitted to different areas throughout the weldment. The amount of stress to be transferred across the joint is estimated using calculations, experience, and so on, as previously discussed. The type of loading and service of the weldment have a great bearing on the joint design that should be selected. All weld joints are either *full-penetration joints* or *partial-penetration joints*. The names are sufficiently descriptive; however, a full-penetration weld joint has weld metal throughout the entire cross section of the weld joint. The partial-penetration joint is designed to have an unfused area. The weld does not penetrate the joint completely. The rating of the joint is based on the percentage of weld metal depth to the total joint. If the weld metal penetrated a quarter of the way

Weld Type	Symbol	The Five Basic Joint Types				
		B Butt	C Corner	E Edge	L Lap	T Tee
Fillet		Special	Yes	Special	Yes	Yes
Plug or slot		–	–	–	Yes	Yes
Spot or projection		–		–	Yes	Special
Seam		–	Special	–	Yes	Special
Square groove		Yes	Yes	Yes	–	Yes
Vee groove		Yes	Yes	Yes	–	Yes
Bevel groove		Yes	Yes	Yes	Yes	Yes
U groove		Yes	Yes	Yes	–	–
J groove		Yes	Yes	Yes	Yes	Yes
Flare V groove		Yes	Yes	–	–	–
Flare bevel groove		Yes	Yes	–	Yes	Yes
Backing weld		Combin.	Combin.	–	–	Combin.
Surfacing		–	–	–	–	–
Flange edge		–	–	Yes	–	–
Flange corner		–	Yes	–	–	–

FIGURE 19-22 Combining table for welds applicable to the basic joints.

from both sides it would still leave half of the joint unfused. A 50% partial-penetration joint would have weld metal halfway through the joint. It was previously mentioned that weldments subjected to static loading need only sufficient weld metal to transfer the static loads. When joints are subjected to dynamic loading, reversing loads, and impact loads the weld joint must be more efficient. This is more important if the weldment is subjected to cold-temperature service. With this type of service the full-penetration weld is required.

The strength of the weld joint depends not only upon the size of the weld but also upon the strength of the weld metal. When using mild and low-alloy steels little thought is given to the strength of the weld metal because the strength of weld metal is normally stronger than the materials being joined. The yield strength of normal structural steel is about 36,000 psi (25.3 kg/mm²). The yield strength for a normal E60XX type of electrode deposit is a minimum of 50,000 psi (35.2 kg/mm²), thus the weld metal is considerably stronger than the base metal. A properly made weld between structural steel members using an E6010 electrode is stronger than the base metal. When this joint is pulled in tension it will always break outside of the weld. The base metal will yield first. The weld metal strength overmatches the base metal in strength and in other mechanical properties. For this reason weld reinforcement should be kept to a minimum since it is not required and is wasteful. In welding high-alloy steel, heat-treated steels, or other heat-treated metals this situation may not apply. Many materials obtain their strength by heat treatment. The weld metal does not have this same heat treatment; therefore, it might have lower strength properties than the base metal. The welding operation might nullify the heat treatment of the base metal causing it to revert to its lower strength adjacent to the weld. When welding high-alloy or heat-treated materials special investigation and precaution must be taken.

Design of the Weld Joint

There are many factors that must be considered in designing a weld joint. Many have an influence on the economics of the weldment design as well as on the strength of the weld joint and the ability of the welder to make it. The designer must take into consideration the strength requirements mentioned here and the penetration requirements dictated by loading and service. The joint design must accommodate these requirements in the most econmical way. This is done by analyzing the following factors.

The weld joint should be designed so that its cross-sectional area is the minimum possible. The cross-sectional area is a measure of the amount or weight of weld metal needed to make the joint. The minimum cross-sectional area, however, may not provide a practical weld joint as discussed later.

Another economic factor has to do with the edge preparation required to produce the particular weld joint design. Weld joints are normally prepared by three methods: shearing, thermal cutting, and machining. They should be considered in this same cost relationship. Shearing is the most economical way to cut metals; however, there are limitations to thickness and the sheared edge is a square cut edge without bevels. Flame cutting is the most popular method of preparation and is used for most work above the gauge metal thicknesses. It can be used for cutting square edges but also for adding bevels. The root face or square edge, the bevel—both front and back, can all be accomplished with one passage of torch assemblies, especially on straight-line cuts. Machining is the third method of preparation but this involves more expensive equipment. Machining is used normally for preparing the J type and U type of preparation. It is popular for preparing weld joints on circular parts. Joint design and metal thickness dictate the type of preparation tools required. Sometimes compromises are made based on the type of tooling available versus the amount of weld metal required to complete the joint.

The individual joint details must also relate to the welding process to be employed. The joint details given later are all related to the shielded metal arc welding process applied manually. This is a good starting point, since designs can be altered to accommodate other processes.

The welding position must also be considered when designing the weld joint. A good example of this is the design of weld joints to splice columns in structural steel buildings. It is good practice to have the bottom side of the joint flat with the bevel on the top piece. This has become standard practice for horizontal welds.

One factor that is sometimes overlooked by designers is the matter of accessibility. The weld joint must be accessible to the welder. Too often, weld joints are designed for welds that cannot be made. Figure 19-23 shows several inaccessible welds. Welds cannot be made on the inside of small-diameter pipe or inside of box columns. The welds in the channel would be very difficult to make in the position shown. Sequence of assembly has an effect on accessibility, but it is advantageous if the weldment can be designed so that all weld joints are accessible for welding after the weldment has been completely assembled and tack welded.

Another factor related to the accessibility problem is the backing or back welding that can be performed on a particular joint. The term *one-side welding* has become very popular since it indicates that the weld is to be completely made on one side of the joint. An example of a one-side weld is the weld on small-diameter pipe. It is impossible to do any work to the back side of such a joint; therefore, the joint must be made completely from the outside of the pipe or a *one-side weld*.

There are many different types of backing. The consumable inserts mentioned previously become part of the

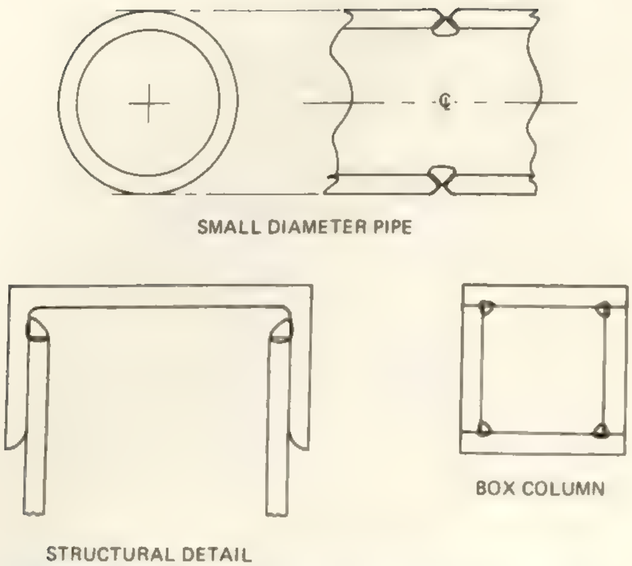
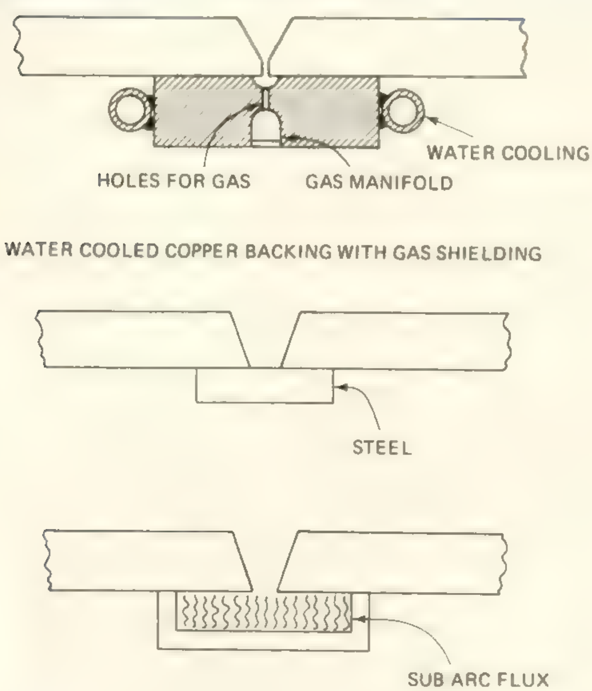


FIGURE 19-23 Inaccessible welds (impossible to make).

joint. Backing straps are beyond the joint but when fused to the root become part of the weldment. Backing straps must be continuous. Fluxes, flux-coated tape, and flux-filled bars are all used for weld backing. Various non-metal items such as ceramic materials and ceramic coated bars can be used as backing materials. Water-cooled copper bars are also used; sometimes they are a part of the fixturing. When used with gas-shielded processes they may incorporate root shielding gas ports. A variety of backing systems are shown in Figure 19-24. If the back side of the joint is accessible it is possible to specify a gouging operation and a backing weld. This is normally a more economical way to weld, but cannot always be utilized.

FIGURE 19-24 Weld backing system.



Consideration should also be given to weld distortion. Study the possibilities of distortion control by means of the use of double welds or welds made on both sides of the center line of the joint to minimize angular distortion. Weld sizes also have an effect on distortion. Use the smallest sizes possible.

On the same general subject is the problem of weld stresses and the possible damage that might occur. This is important when welding high-strength materials in which brittle fracture may be involved. Consideration must be given to lamellar tearing of the base metal directly under the weld, which might be harmful.

Fillet Weld Design

The fillet weld is the most popular of all welds because there is normally no preparation required. In some cases, the fillet weld is the least expensive, even though it might require more filler metal than a groove weld since the preparation cost would be less. It can be used for the lap joint, the T joint, and the corner joint without preparation. On corner joints the double fillet can actually produce a full-penetration weld joint. The use of the fillet for making the basic joints is shown in Figure 19-25. Fillet welds are also used in conjunction with groove welds, particularly for corner and tee joints.

The fillet weld is expected to have equal-length legs and thus the face of the fillet is on a 45° angle. This is not always so since a fillet may be designed to have a longer base than height in which case it is specified by the two leg lengths. On the 45° or normal type of fillet the strength of the fillet is based on the shortest or throat dimension which is 0.707 × the leg length. In North America, fillet welds are specified by the leg length, whereas in many European countries they are specified by the throat dimension. For fillets having unequal legs the throat length must be calculated and is the shortest distance between the root of the fillet and the theoretical face of the fillet. In calculating the strength of fillet welds the reinforcement is ignored. Also the root penetration is ignored unless a deep penetrating process is used. If semi- or fully automatic application is used, the extra penetration can be considered. See Figure 19-26 for details about the weld.

Under these circumstances the size of the fillet can be reduced yet equal strength will result. Such reductions can be utilized only when strict welding procedures are enforced. The strength of the fillet weld is determined by its failure area, which relates to the throat dimension. Doubling the size (leg length) of a fillet will double its

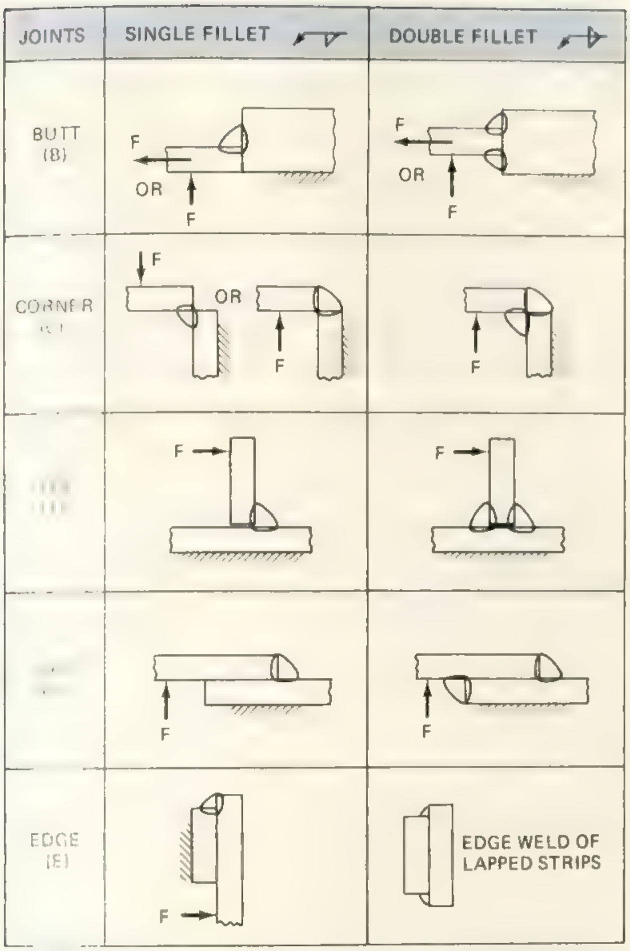


FIGURE 19-25 **Fillet used to make the five basic joints.**

strength, since it doubles the throat dimension (and area). However, doubling the fillet size will increase its cross-sectional area and weight four times. This is illustrated by Figure 19-27, which shows the relationship to throat-versus-cross-sectional area or weight of a fillet weld. For example, a ⅜-in. fillet is twice as strong as a $\frac{3}{16}$-in. fillet; however, the ⅜-in. fillet requires four times as much weld metal.

In design work the fillet size is sometimes governed by the thickness of the metals joined. And in some situations the minimum size of the fillet must be based on practical reasons rather than the theoretical need of the design. Intermittent fillets are sometimes used when the size is minimum, based on code, or for practical reasons, rather than because of strength requirements. Many intermittent welds are based on a pitch and length so that the weld metal is reduced in half. Large intermittent fillets are not recommended because of the volume–throat dimension relationship mentioned previously. For example, a ⅜-in. fillet 6 in. long on a 12-in. pitch (center to

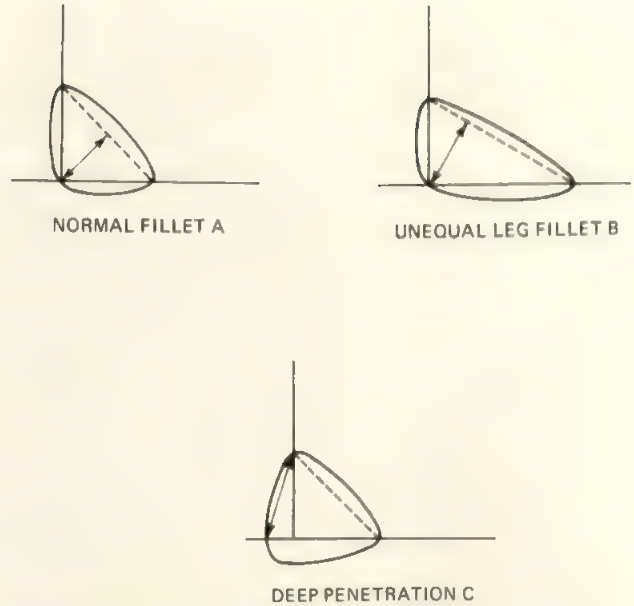
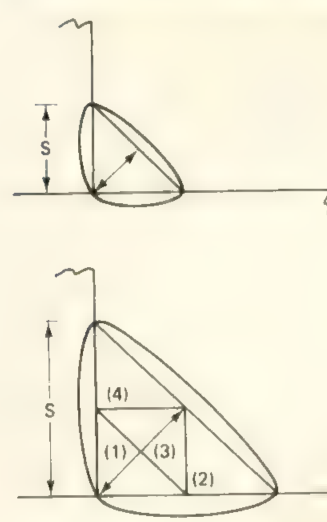


FIGURE 19-26 **Fillet weld throat dimension.**

center of intermittent welds) could be reduced to a continuous $\frac{3}{16}$-in. fillet and the strength would be the same, but the amount of weld metal would be only one half as much.

Single fillet welds are extremely vulnerable to cracking if the root of the weld is subjected to tension loading. This applies to tee joints, corner joints, and lap joints. The simple remedy for such joints is to make double fillets, which prohibit the tensile load from being ap-

FIGURE 19-27 **Fillet weld size versus strength.**



plied to the root of the fillet. This is shown by Figure 19-25. Notice the F (force) arrowhead.

Groove Weld Design

There are seven basic types of the groove weld. The square, V, bevel, U, J, flare V, and flare bevel are shown by Figure 19-28. They can all be used singly or as double welds. Three of them, the square groove, the flare V, and the flare bevel groove weld, can be made without extra preparation of the joint detail. The square groove is the simplest, since it requires only a square cutoff and for thinner metals this is accomplished by shearing. The scarf is a variation of the square groove used for brazing. The flare V and flare bevel welds are normally used for thinner materials in which a bent section joins another section or in which a round section is involved. Two of the other groove welds require preparation on only one of the members of the joint and these are the bevel groove weld and the J groove weld. The remaining two, the V groove and the U groove welds, require preparation of both members of the joint.

There are several names given to groove weld designs that are not standard with AWS. These names, used mostly in Europe, are descriptive and deserve mention. Some of the more common names are X, K, and

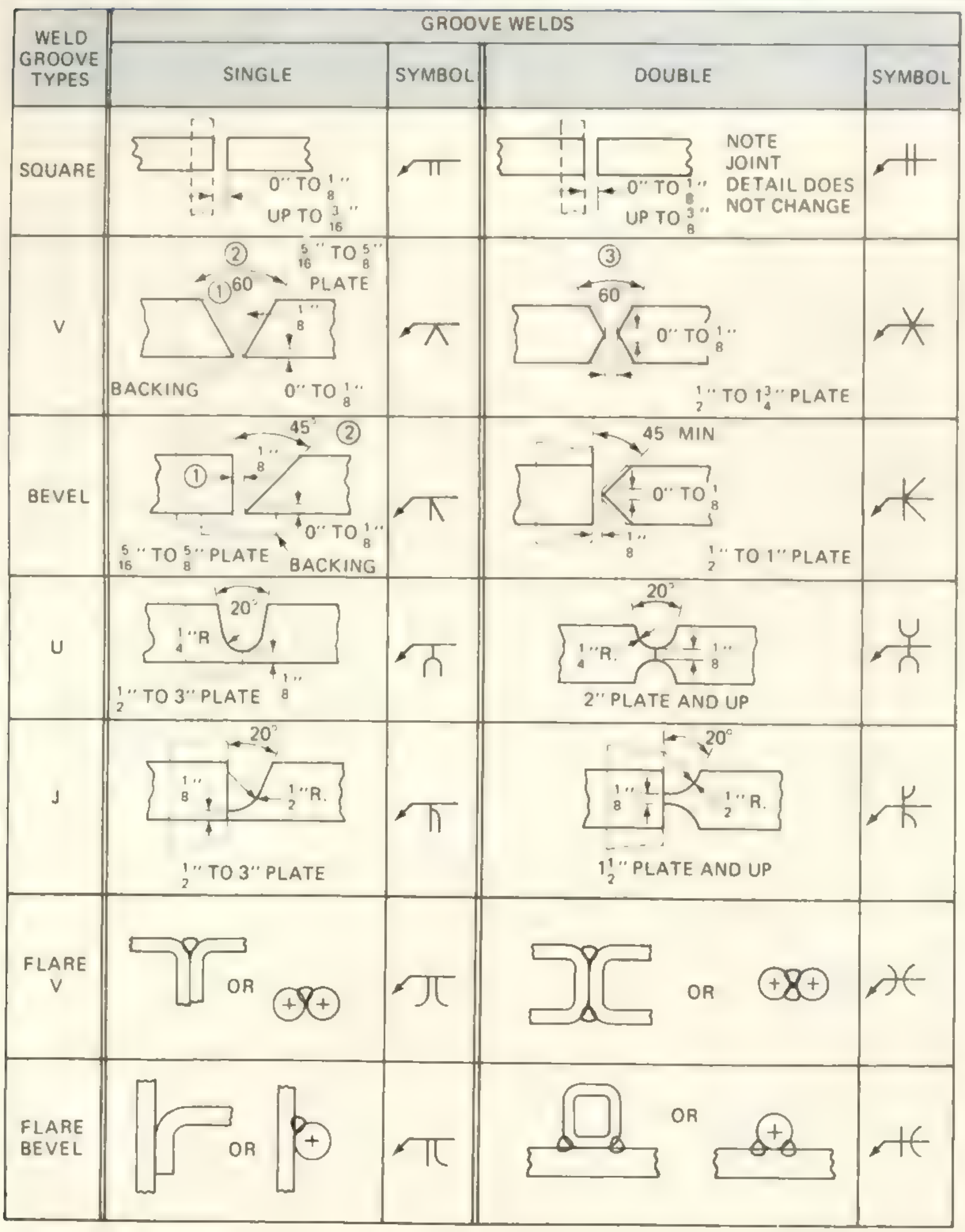


FIGURE 19-28 Seven basic types of groove welds.

Y grooves. These letters describe the weld in cross section. The X weld is a double vee weld without a root face. The K weld is a double bevel weld and the Y weld is a single vee with a relatively large root face. Draw these in cross section and you will see the resemblance to these letters.

Preparation can become a major factor in deciding which of the groove types to use. For example, the square groove can be prepared by shearing if the metal is relatively thin. The square groove preparation is also used on thick materials for the electroslag process and other *narrow gap* processes. When the thickness is too great, preparation would be by flame cutting. The flare V joints can be made with thin material flanged by a brake press or with square or rectangular mechanical tubing. They are also used when two intersecting round sections are welded together such as the welding of reinforcing bars or rods together. The flare bevel weld is similar, except that only one member has the radius. The bevel and V groove welds are normally used for medium to thicker materials and flame cutting would be required. For the heavier plate the double V or double bevel groove would be used and flame cutting would be employed. The choice between single and double groove welds is shown in Figure 19-28. In both the V groove and bevel groove a root face may or may not be involved. The normal practice is to have a small root face which helps provide dimensional control of the parts during parts preparation operations. The J groove design requires the J-type preparation on one of the parts whether a single or a double J is used. In the case of the U groove both members must have the special curved shape which involves either machining or special gouging and cutting. The other groove designs are also easier to make on circular parts.

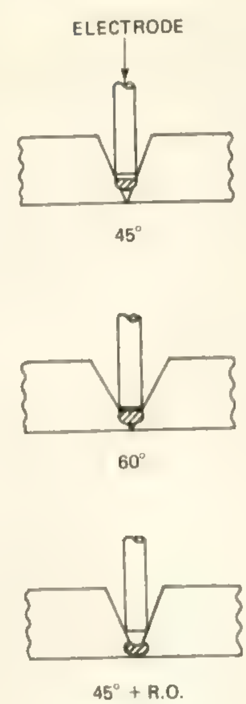
The root face mentioned above is used primarily to assure dimensional control of the parts during the parts preparation operation. When large plates are flame cut to feather edges, either V or bevel joint preparations, it is more difficult to hold dimensions than if a root face is involved. However, to obtain two surfaces on the edge requires two passages of the cutting torch unless an existing square edge is used. The root face should be kept to a minimum where full joint penetration is required. When partial penetration is required the root face can be quite large but rarely over 50% of the thickness of the part being beveled. In weldments for which stiffness and weight are the primary criteria, and if dynamic loading is not involved, large root faces will save a considerable amount of weld metal and make the joint less expensive.

There are two other factors that must be considered with respect to the V and bevel groove welds. They must be considered together since they do affect the welder's ability to make or place a weld bead at the root of the joint. These are the included angle and the root opening. In full-penetration welds it is absolutely necessary that the welder have sufficient room and accessibility to place the weld at the root of the joint. If the root opening is too tight or if the included angle is too narrow, it will be impossible for the welding electrode to deposit the weld metal at the root of the joint (Figure 19-29). It is obvious that one or the other must be widened to allow the root weld to be made. The illustration shows what is accomplished by increasing the included angle, but the best solution is accomplished by increasing the root opening. There are optimum included angles and root openings for shielded metal arc welding and these are based on producing a completely fused root pass. The sample designs shown later utilize these optimum or standardized angles. For different processes these vary.

The J and U groove welds have been fairly well standardized in design. This means that the radius at the root and the included angle have been optimized and these are shown by the examples later in this chapter. Finally, for certain metals and for certain applications special joint details are used. For example, for aluminum pipe a broad single-U preparation is used so that the root is similar to a thinner member which can readily be fused together when making the root pass. In heavy-wall pipe, compound angles are often used when the joints are prepared by machining. Figure 19-30 shows the relationship of cross-sectional area for single and double welds and when the root opening is increased.

Finally, when using groove welds on corner and tee

FIGURE 19-29 Groove weld root opening–included angle relationship.



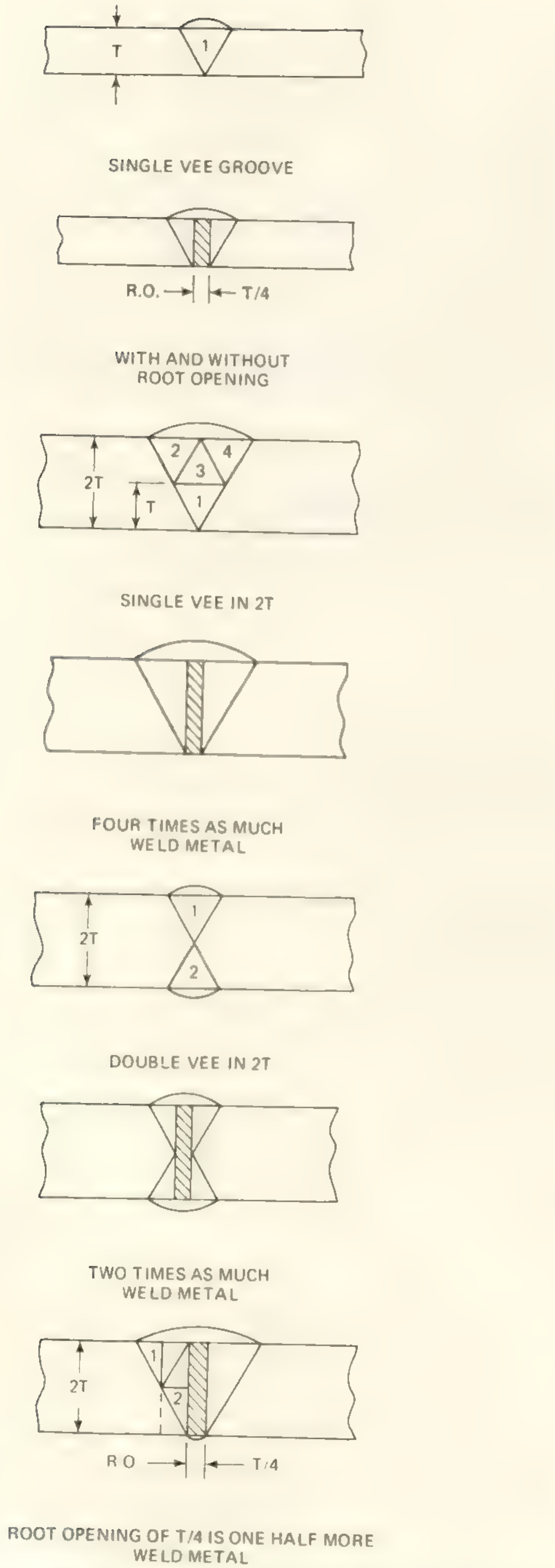


FIGURE 19-30 Summary of groove weld design dimensions.

joints, fillets may be used for reinforcement to avoid sharp changes of direction and stress concentrations.

The problem of joint design can sometimes be compounded in the weldment, if fit is not as designed. Unfortunately, in many shop situations root openings are sometimes used to accommodate tolerances of flame cut parts. If the part is larger than it should be the root openings will disappear and the ability for the welder to make a full penetration weld is reduced. This is why inspection of tacked up weldments can detect potential problems and eliminate defective welds. If the parts come too small, the root openings will be excessively large and extra weld metal is required to make the weld joint. This is expensive and sometimes it is more economical to remake a piece than to fill in a larger than designed groove. If the root opening and the overall joint design is adversely affected by these manufacturing tolerances, it will be necessary to retrim the parts according to their original design or remake the part to its original design so that the weld joint preparation is in accordance with the design.

Other Weld Designs

Plug and slot welds and spot and seam welds can be used for lap joints, tee joints, and corner joints. Seam welds and spot welds can be made with resistance welding processes and arc welding processes. In this chapter we are interested primarily in the weld joints that are designed for the shielded metal arc or other arc welding processes. The seam welds and the spot welds, when using the arc processes, are made by melting through the top member of the joint into the other members. These are sometimes called *burn-through* welds. They are restricted to thin materials and are largely dependent on the depth of penetration of the process involved. They are quite popular for the CO_2 welding process, which has deep penetrating qualities. The joint strength is based on the area of the weld at the interface between the two members. The way these and the other weld types are applied to the five basic joint types is shown in Figure 19-31.

Plug and slot welds have holes prepared in one member so that the welding can be done through the hole into the other member. Plug welds are round and slot welds are elongated. The holes are completely filled in making the plug or slot welds. Plug welds were made in early design transitions from riveted structures to welded structures. As designs have improved, the plug welds have been discontinued. They are, however, used for certain blind applications in which the other side of the weld joint may be inaccessible.

Standard dimensions have been established for plug or slot welds (Figure 19-32). The strength of these welds is obtained by calculating the area of the plug hole or slot hole where it interfaces the other member.

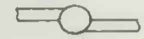
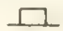
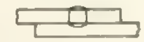
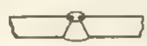
OTHER WELD TYPES	SYMBOL	THE FIVE BASIC JOINT TYPES				
		BUTT (B) 	CORNER (C) 	TEE (T) 	LAP (L) 	EDGE (E) 
PLUG OR SLOT WELD		NO				NOT APPLICABLE
SPOT OR PROJECTION (ARC OR RESISTANCE)		NO				NOT APPLICABLE
SEAM WELD (ARC OR RESISTANCE)		NO				NOT APPLICABLE
BACK OR BACKING WELD					NOT APPLICABLE	NOT APPLICABLE
SURFACING		NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE
FLANGE WELD EDGE (SHEET METAL)		NO	NO	NO	NO	
FLANGE WELD-CORNER (SHEET METAL)		NO		NO	NO	NO

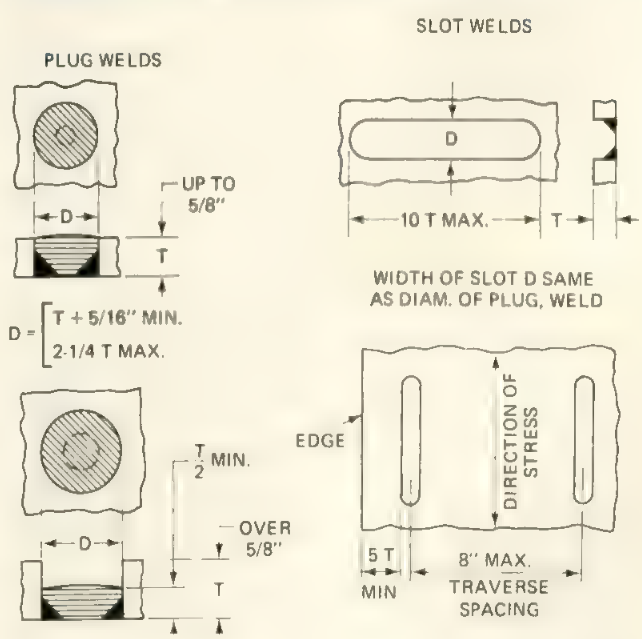
FIGURE 19-31 Other types of welds related to the five basic joints.

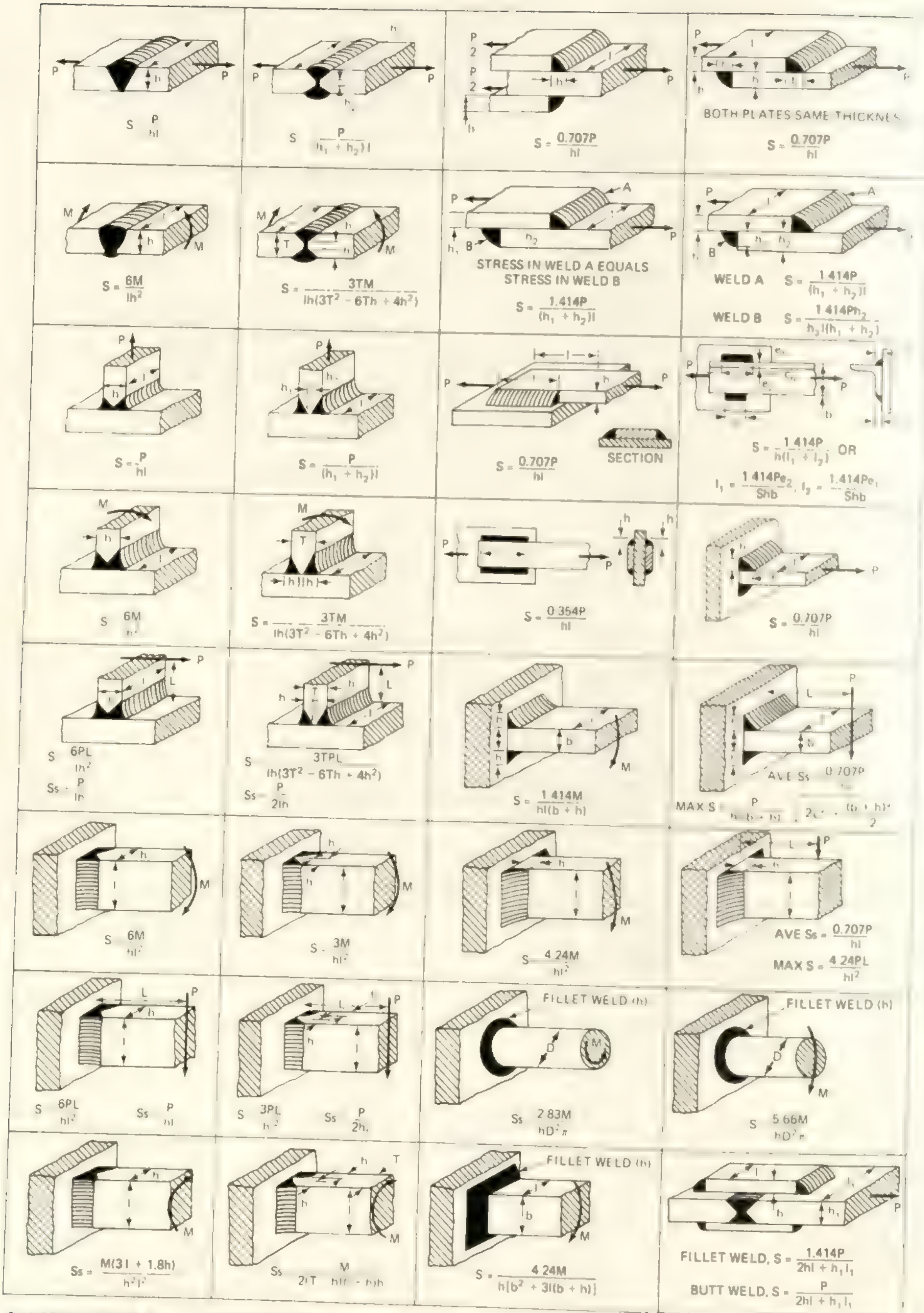
Surfacing welds are normally bead welds made on a surface to provide special properties or dimensions of that surface. They are commonly used to build up areas for remachining, to provide corrosion-resistant surfaces, or to provide abrasion-resistant or hard surfaces for wear. Surfacing welds can be made using most of the arc processes and with strip electrode shielded by submerged arc flux to provide wider beads. They do not involve the making of joints.

The flange weld edge and corner joints are used primarily for lighter gauge metals, usually called sheet metals. Flanging of parts at welds is common practice to improve stiffness, reduce distortion, and to provide an area for welding. The only preparation involved is shearing and bending.

The last of the weld types is the back or backing weld which is used primarily for improving the properties of the root of the single groove welds. To perform the back or backing weld the back side of the weld must be accessible. It is used to ensure that root fusion is complete and that any potential stress risers are eliminated.

FIGURE 19-32 Plug and slot weld designs.





S = NORMAL STRESS, PSI
Ss = UNIT STRESS, PSI
I = MOMENT OF INERTIA, INCH UNITS
M = BENDING MOMENT, IN LB
D = EXTERNAL LOAD, LB
L = LINEAR DISTANCE
H = SIZE OF WELD
l = LENGTH OF WELD, IN

FIGURE 19-33 Summary of formulas used to determine allowable stresses. (From Ref. 3.)

Gouging, chipping, or grinding is performed before the backing weld is made. A summary of formulas used to determine stresses in welds for different welds and different joints and loadings is given in Figure 19-33.[3]

Weld Joint Details

The following illustrations of joint designs will provide a ready reference for the designer. These joint designs are based on the requirements of the American Welding Society's structural code and include the details of the joint, the joint limitations, its use, and the welding symbol.[4] These joint designs are for use with the shielded metal arc welding process and have been prequalified for this process. The joint designs are suitable for oxyacetylene welding, gas tungsten arc welding, gas metal arc welding, and flux-cored arc welding. However, modifications can be made on these joint designs if they are to be used exclusively for one specific welding process. These changes would make the joints more economical when they are used with a specific process. To obtain efficient, economical weld joint designs the designer must follow the recommended limitations on material thickness. One joint design may be optimum for thin material but poor on thick material.

The weld joint details are indexed by a code system which will identify the type of joint, the material thickness limitation, joint penetration requirement, and the type of weld. Similar weld designs are then expanded alphabetically to provide variations (Figure 19-34). This system is similar to that of "Welded Joint Design," MIL-STD-0022B (SHIPS), but sufficiently different so that the numbering system is not interchangeable.[5] A similar system is presented by the American Institute of Steel Construction.[6]

Figure 19-35 presents the series of weld joint details indexed by this code system. In this identification system, the joint type is first. The types of joints are listed alphabetically; thus the butt joints (B) come first followed by corner joints (C), and so on. Combination joints are also included since the weld detail can be the same for more than one type of joint.

The second factor is the material thickness and penetration requirements. There are three categories. L indicates limited thickness. A maximum nominal thickness is shown for each particular joint. In these cases the thickness maximum must be adhered to. U indicates unlimited thickness. This would be used for materials thicker than the L category. P indicates partial penetration. In these joint designs a sufficiently large root face is used to avoid complete penetration. Caution must be exercised when using partial penetration joints in which dynamic loading and cold temperature service are involved.

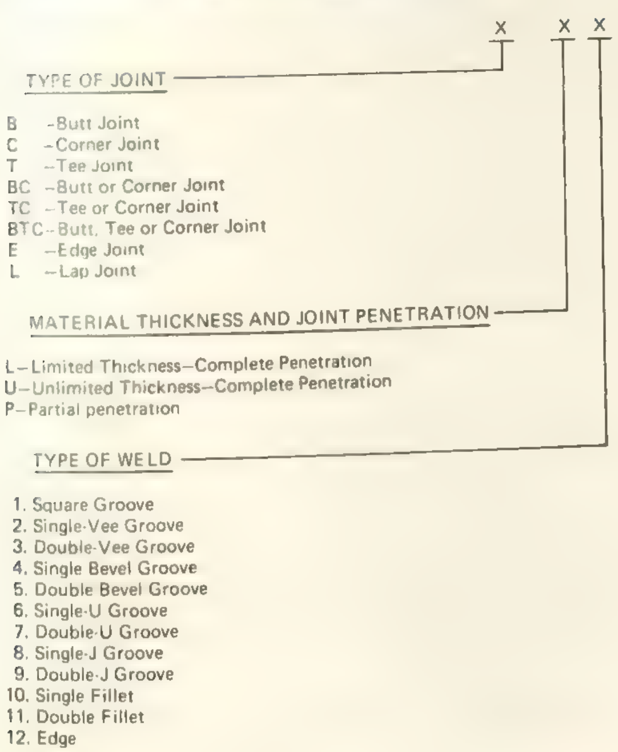
The third factor is the type of weld. These are based on the types of weld groove and welds. When using these joint designs, the following allowable variations of dimensions should be observed. The root face (RF) of joints is zero unless dimensioned otherwise. If the dimension is zero or otherwise, the root face should not exceed the dimension shown by more than $\frac{1}{16}$ in.

The root opening (RO) of joints shown is minimum. Root opening should not exceed the dimension shown by more than $\frac{1}{16}$ in. The groove angle (A) shown is minimum. The angle dimension should not be exceeded by more than $+10°$ or $-0°$. The radius (R) dimension of J and U grooves is minimum. This minimum dimension should not be exceeded by more than $\frac{1}{8}$ in. Single-bevel and single-J groove weld joints should not be used for butt joints except in the horizontal position and in this case the beveled or grooved part must be the upper member of the joint.

Double-groove welds may have grooves of unequal depths. The depth of a shallower groove should not be less than one-fourth the thickness of the thinner member joined.

In composite welds where fillet welds are used to reinforce groove welds, particularly in T and corner joints, the size of the fillet should equal T/4 of the thinner member but should not exceed $\frac{3}{8}$ in. maximum. For more detailed information and additional joints, refer to the American Welding Society's structural welding code.

FIGURE 19-34 Weld joint identification number.



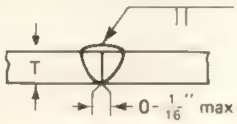
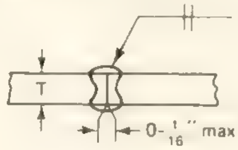
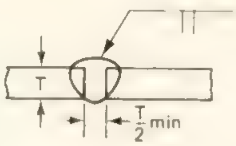
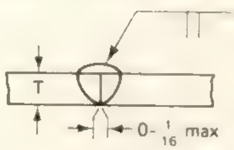
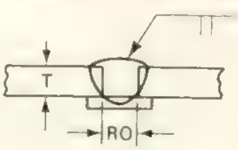
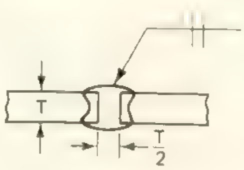
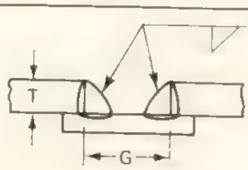
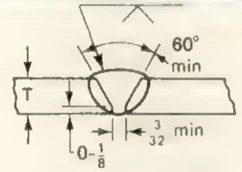
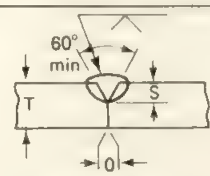
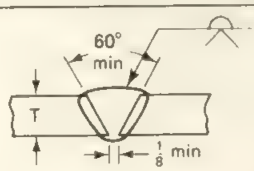
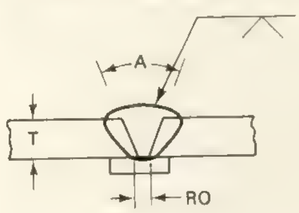
Butt Joints (B)	
B-Pla  T max. = $\frac{1}{8}$"	Partial penetrating, square groove weld, weld one side: 1. Effective throat thickness shall be taken as one half the thickness of the thinner part joined. 2. Shall not be used when root of weld is subject to tension. 3. Suitable for all types of loading except fatigue loading and high transverse loads.
B Plb  T max. = $\frac{1}{4}$"	Partial penetrating, square groove weld, weld both sides 1. Effective throat thickness shall be taken as three fourths the thickness of the thinner part joined 2. Root opening not more than $\frac{1}{16}$" 3. Gouging or chipping out the back side of the root pass is not required. 4. Suitable for all types of loading except fatigue loading and high transverse loads.
B Plc  T max. = $\frac{1}{4}$"	Partial penetrating, open square groove weld, weld one side 1. Effective throat thickness shall be taken as three fourths the thickness of the thinner part joined. 2. Root opening not less than one half the thickness of the thinner part joined. 3. Shall not be used when root of weld is subject to tension. 4. Suitable for all types of loading except fatigue loading and high transverse loads.
B Pld  T max = $\frac{1}{4}$"	Partial penetrating square groove weld, weld one side: 1. Effective throat thickness shall be taken as 85% the thickness of the thinner part joined up to $\frac{3}{16}$" maximum thickness. 2. Effective throat thickness for $\frac{1}{4}$" thickness shall be taken as $\frac{1}{8}$". 3. Shall not be used when root of weld is subject to tension.
B Lla  T max. = $\frac{1}{4}$"	Open square groove weld, weld one side on backing strip 1. Effective throat thickness 100% thinner part joined 2. #16 gauge material is approximate minimum value of T. 3. Backing strip should be in form of a stiffner whenever possible.
B Llb  T max = $\frac{1}{4}$"	Open square groove weld, weld both sides. 1. Effective throat thickness shall be taken as 100% of the thinner part joined. 2. Gouging or chipping out of the back side of the root pass is not necessary.
B Llc  T max. = $\frac{1}{4}$" G min. = 2T + $\frac{1}{8}$"	Open square groove weld, weld one side on backing strip: 1. Effective throat thickness is determined by weld size. 2. Shall not be used when root of weld is subject to tension bending. 3. May be used for sealing against water. 4. May be used to allow for variations in sheet sizes. 5. Uneconomical in thickness less than $\frac{3}{16}$" 6. Backing strip should be in form of a stiffner whenever possible.

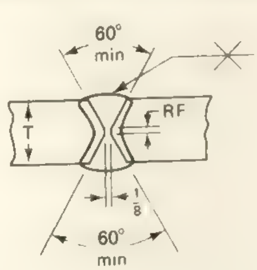
FIGURE 19-35 **Weld joint designs.**

<table>
<tr><th colspan="2">Butt Joints (B)</th></tr>
<tr><td>B-P2a


T max. = 1/2"</td><td>Partial penetrating single vee-groove weld, welded from one side.
1. The effective throat thickness shall be taken as three fourths the thickness of the thinner part joined.
2. Shall not be used where root of weld is subject to tension bending.
3. Shall not be used when subject to fatigue, impact loading, or service at low temperature.
4. Preparation and welding relatively inexpensive.</td></tr>
<tr><td>BC-P2


T greater than 1/2"</td><td>Partial penetrating single vee-groove welds in butt and corner joints, welded from one side:
1. For material thicknesses greater than one half inch.
2. The minimum effective throat thickness shall be T/6 where T is the thickness of the thinner part joined.
3. The effective throat thickness shall be taken as S-1/4", where S is the depth of the groove, or size.
4. Shall not be used where root of weld is subject to tension bending.
5. Shall not be used when subject to fatigue, impact loading, or service at low temperature.
6. Preparation and welding inexpensive.</td></tr>
<tr><td>B-L2


T max. = 3/4"</td><td>Single vee groove weld, welded from both sides:
1. Effective throat thickness shall be taken as the thickness of the thinner part joined.
2. Economical for thicknesses (T) between 1/4 and 3/4 inch from a standpoint of welding required.</td></tr>
<tr><td>B-U2


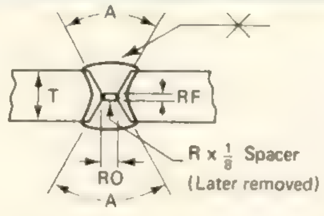
"T" unlimited
<table>
<tr><th colspan="3">Joint Limitations</th></tr>
<tr><th>A</th><th>RO</th><th>Permitted welding positions</th></tr>
<tr><td>45°</td><td>1/4</td><td>All positions</td></tr>
<tr><td>30°</td><td>3/8</td><td>Flat and overhead only</td></tr>
<tr><td>20°</td><td>1/2</td><td>Flat and overhead only</td></tr>
</table></td><td>Single vee-groove weld, welded from one side with backing strip:
1. T is unlimited; other joint limitations appear in table at left.
2. Effective throat thickness shall be taken as the thickness of the thinner part joined.
3. May be used for all position welding except horizontal.
4. Shall be used only when back side of joint is inaccessible.
5. The adjacent structure should be designed so as to resist angular distortion whenever possible.
6. Joint with 20° groove angle should only be used for highly critical joints subject to impact and/or fatigue loads.
7. Do not use in corrosive service unless backing is removed.
8. Economical for thicknesses T from 1/4 to 3/4 inch from a standpoint of welding required.</td></tr>
<tr><td>B U3b


Approx. minimum T = 5/8"</td><td>Double-vee groove weld
1. Root face (R.F.) dimension range is from 0 to 1/16 inch.
2. Full strength obtainable for all types of loading.
3. Economical for thicknesses from 3/4 to 1-1/2 inch from a standpoint of welding required
4. To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.
5. May be used where the joint is totally unrestrained against angular distortion.</td></tr>
</table>

FIGURE 19-35 *(cont.)*

Butt Joints (B)

B-U3a

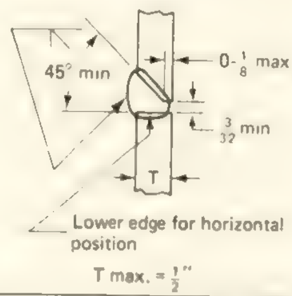


A	RO	Permitted welding positions
45°	1/4	All positions
30°	3/8	Flat and overhead
20°	1/2	Flat and overhead

Double-vee groove weld:

1. Full strength obtainable for all types of loading.
2. To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.
3. May be used where joint is totally unrestrained against angular distortion.
4. Approximate minimum thickness T equals $\frac{5}{8}$"

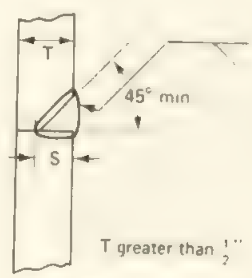
B P4



Partial penetrating, single bevel groove weld, welded from one side:

1. May be used for horizontal joints.
2. Effective throat thickness shall be taken as three fourths the thickness of the thinner part joined
3. Shall not be used when root of weld is subject to tension bending.
4. Shall not be used when subject to impact and/or fatigue loads.
5. Should be used only where design of the structure will resist angular distortion of the joint or where angular distortion is not detrimental.

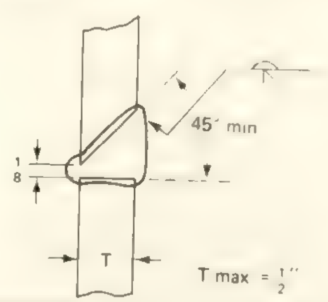
BTC P4



Partial penetrating, single bevel groove weld, welded from one side

1. For T greater than $\frac{1}{2}$ inch.
2. The minimum effective throat thickness shall be T/6 where T is the thickness of the thinner part joined
3. The effective throat thickness shall be taken as $\frac{1}{4}$ inch less than the depth of the groove
4. May be used for horizontal joints.
5. Shall not be used when root of weld is subject to tension bending.
6. Shall not be used when subject to impact and/or fatigue loads.
7. Should be used only where design of the structure will resist angular distortion of the joint or where angular distortion is not detrimental

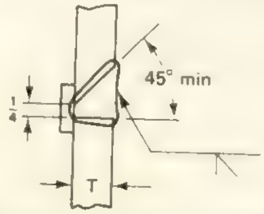
B L4



Single bevel groove weld, welded from both sides

1. The effective throat thickness shall be taken as the thickness of the thinner part joined.
2. To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.
3. May be used for horizontal joints.
4. Shall not be used when root of weld is subject to tension bending.
5. Shall not be used when subject to impact and/or fatigue loads.
6. Should be used only where design of the structure will resist angular distortion of the joint or where angular distortion is not detrimental.

B-U4



Single bevel groove weld, welded from one side with back up strip:

1. May be used for horizontal joints.
2. Shall be used only when the back side of the joint is inaccessible.
3. Adjacent structure should be designed so as to resist angular distortion whenever possible.

FIGURE 19-35 *(cont.)*

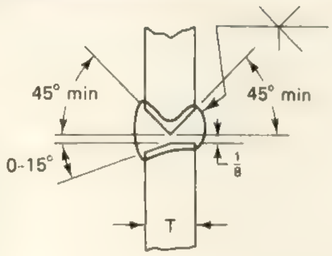
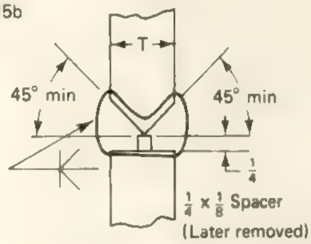
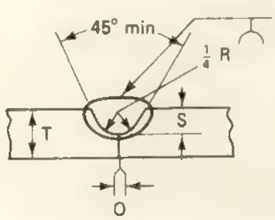
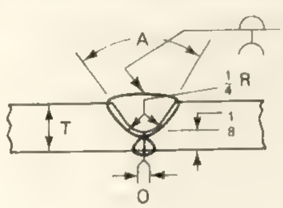
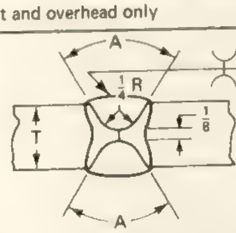
Butt Joints (B)	
B-U5a  Min. recommended T = $\frac{5}{8}''$	Double bevel groove weld: 1. May be used in horizontal position. 2. Root of first weld should be gouged out to sound metal before depositing second weld. 3. May be used where joint is totally unrestrained against angular distortion. 4. Economical from a welding standpoint for thicknesses up to $1\text{-}\frac{1}{2}''$
B-U5b  Minimum recommended T = $\frac{5}{8}''$	Double bevel groove weld with spacer: 1. May be used in horizontal position. 2. May be used where joint is totally unrestrained against angular distortion. 3. Economical from a welding standpoint for thicknesses up to $1\text{-}\frac{1}{2}''$.
BC-P6 	Partial penetrating, single U-groove weld, welded from one side: 1. The minimum effective throat, thickness shall be T/6 where T is the thickness of the thinner part joined. 2. The effective throat thickness shall be taken as the full depth of the groove. 3. Joint preparation is expensive. 4. Shall not be used when root of weld is subject to tension bending.
B U6  A | Permitted welding positions 45° | All positions 20° | Flat and overhead only	Single U-groove weld, welded from both sides: 1. Full strength obtainable for all types of loading. 2. Economical from standpoints of ease of welding and welding required when thickness is greater than $\frac{3}{4}''$ However, joint preparation is expensive. 3. To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.
B-U7  Minimum recommended T = $\frac{5}{8}''$ A | Permitted welding positions 45° | All positions 20° | Flat and overhead only	Double U-groove weld, welded from both sides: 1. Full strength obtainable for all types of loading. 2. To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld. 3. Most easily welded groove, however it is expensive to prepare. 4. Most economical from a standpoint of welding required when thickness exceeds $1\text{-}\frac{1}{2}$ inches. However, the minimum thickness should be $\frac{5}{8}$ inch.

FIGURE 19-35 *(cont.)*

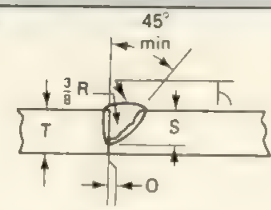
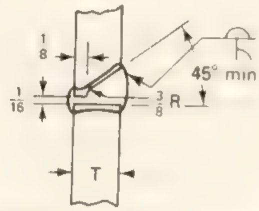
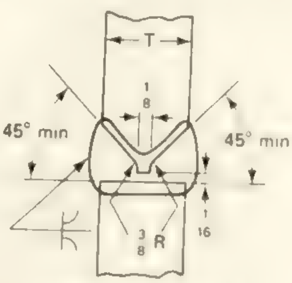
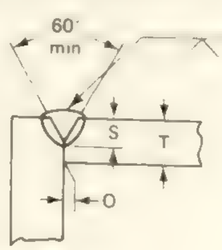
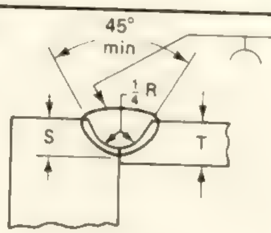
Butt Joints (B)	
BTC-P8  T greater than $\frac{1}{2}$"	Partial penetrating, single J-groove weld, welded one side: 1. The minimum effective throat thickness shall be T/6 where T is the thickness of the thinner part joined. 2. The effective throat thickness shall be taken as the depth of the groove. 3. Expensive joint to prepare. 4. Should not be used when root of weld is subject to tension bending.
B-U8 	Single J-groove weld, welded from both sides 1. Shall be used in horizontal joints only. 2. Full strength obtainable for all types of loading 3. Expensive joint to prepare. 4. Economical from a welding standpoint of filler metal required when the thickness exceeds $\frac{3}{4}$ inch. 5. To obtain full strength for all types of loading the root of the first weld should be chipped out to sound metal before depositing the second weld.
B U9  Min recommended T - $\frac{5}{8}$"	Double J-groove weld, welded from both sides: 1. Shall be used for horizontal joints only. 2. Difficult to obtain a sound weld due to perpendicular groove face. 3. To obtain full strength for all types of loading, the root of the first weld should be chipped out to sound metal before depositing the second weld. 4. Expensive to prepare. However, it becomes economical from a standpoint of welding required when the depth of chamfering on each side exceeds $\frac{3}{4}$" 5. The approximate minimum base metal thickness should be $\frac{5}{8}$"
Corner Joints (C)	
BC P2  T greater than $\frac{1}{2}$"	Partial penetrating single vee-groove welds in butt and corner joints, welded from one side 1. For material thicknesses greater than one half inch. 2. The minimum effective throat thickness shall be T/6 where T is the thickness of the thinner part joined. 3. The effective throat thickness shall be taken as D-$\frac{1}{4}$" where D is the depth of the groove. 4. Shall not be used where root of weld is subject to tension bending. 5. Shall not be used when subject to fatigue, impact loading, or service at low temperature. 6. Preparation and welding inexpensive.
BC-P6  T greater than $\frac{1}{2}$"	Partial penetrating, single U groove weld, welded from one side: 1. The minimum effective throat thickness shall be T/6 where "T" is the thickness of the thinner part joined. 2. The effective throat thickness shall be taken as the full depth of the groove. 3. Joint preparation is expensive. 4. Shall not be used when root of weld is subject to tension bending.

FIGURE 19-35 *(cont.)*

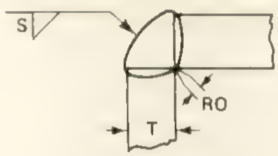
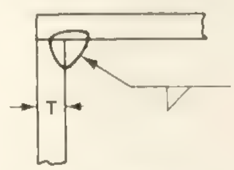
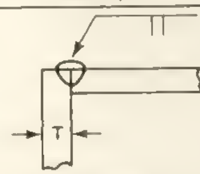
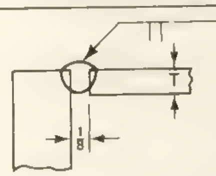
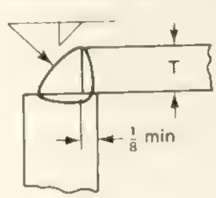
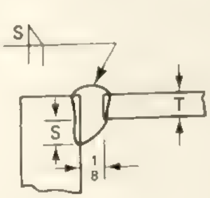
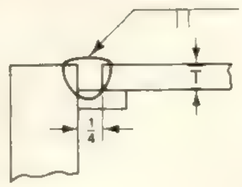
Corner Joints (C)	
C-P  T min = #12 gauge T max = $\frac{3}{4}$ inch RO = 0 for T = 1/4 or less 1/16 for T = 1/2 or less 1/8 for T = 5/8 or less	Partial penetrating outside single fillet welded corner joint: 1. 70% effective throat thickness when S = T. 2. Shall not be used when root of weld is subject to tension bending. 3. Should not be used when subject to impact and/or fatigue if direction of loading is transverse to axis of the weld. 4. Design for zero root opening except for $\frac{1}{8}''$ gap in which case $\frac{1}{16}''$ shall be allowed for each plate.
C-P1  T min. = 16 gauge T max. = $\frac{1}{4}''$	Partial penetrating square groove corner joint, inside fillet weld: 1. Efficiency determined by weld size. 2. Used intermittent welds whenever possible. 3. Shall not be used whenever root of weld is subject to tension bending. 4. Should be used whenever good appearance of the outside corner must be maintained.
C-Pla  T max = #16 ga.	Partial penetrating square groove weld, welded from one side: 1. Shall be used only when the inside of the joint is inaccessible for welding or when the appearance of the outside corner is not critical. 2. Should not be used when root of weld is subject to tension bending.
C-Plb 	Partial penetrating open square groove weld, welded from one side: 1. The effective throat thickness shall be taken as 3/4 T. 2. Shall not be used when root of weld is subject to tension bending. 3. Should be used only when surface across joint is required to be relatively flush.
C-P1c  T min = #16 gauge T max = $\frac{3}{4}$ inch	Partial penetrating outside single fillet welded corner joint: 1. Effective throat thickness determined by weld size. 2. Shall not be used when root of weld is subject to tension bending. 3. Should not be used when subject to impact and/or fatigue if direction of loading is transverse to axis of the weld. 4. Overlap facilitates set-up and allows for variations in plate size. 5. Strength may be increased by adding continuous or inter mittent fillets on the far side of the joint if accessible when T is $\frac{1}{4}''$ or greater.
C-L1  Max. T = $\frac{1}{4}''$ Max. S recommended = $\frac{3}{16}''$	Open square groove weld with fillet weld reinforcement: 1. Should use joint C-L1a when back side is not accessible and 100% effective throat thickness is required. 2. Should only be used when surface across joint is required to be relatively flush.

FIGURE 19-35 *(cont.)*

Corner Joints (C)

C-L1a

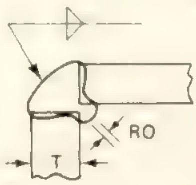


Max. T = $\frac{1}{4}''$

Open square groove weld with back-up strip:

1. Recommended size for back-up strip, $\frac{3}{8}'' \times \frac{3}{8}''$.
2. Should be used only when the full strength of the thinner plate need be developed.

C



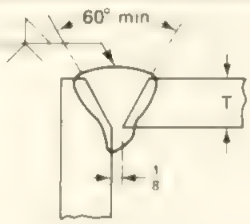
S = T/2

RO = 0 for T = 1/4 or less
1/16 for T = 1/2 or less
1/8 for T = 5/8 or greater

Double fillet welded corner joint:

1. Effective throat thickness determined by weld size.
2. Design for zero root opening except for $\frac{1}{8}$ inch opening in which case $\frac{1}{16}$ inch shall be allowed for each plate

C-L2

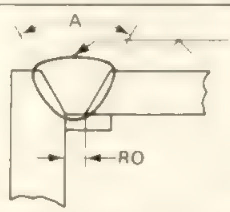


T = $\frac{3}{4}$ max

Single vee groove weld, welded from both sides:

1. Effective throat thickness shall be taken as the thickness of the thinner part joined.
2. Shall not be used when tension due to bending is concentrated at the root of the weld.
3. Shall not be used when subject to fatigue, impact loading, or service at low temperature.
4. Economical for thicknesses T between $\frac{1}{4}$ and $\frac{3}{4}$ inch from a standpoint of welding required.

C-U2



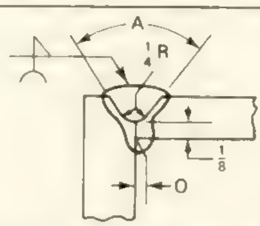
A	RO	Permitted welding positions
45°	1/4	All positions
30°	3/8	Flat and overhead only
20°	1/2	Flat and overhead only

Single vee groove weld with back up strip:

1. T is unlimited; other joint limitations appear in table at left.
2. Effective throat thickness shall be taken as the thickness of the thinner part joined.
3. May be used for all position welding except horizontal
4. Shall be used only when back side of joint is inaccessible
5. The adjacent structure should be designed so as to resist angular distortion whenever possible.
6. Joint with 20° groove angle should only be used for highly critical joints subject to impact and/or fatigue loads.
7. Do not use in corrosive service unless backing is removed
8. Economical for thicknesses from $\frac{1}{4}$ to $\frac{3}{4}$ inch from a standpoint of welding required.

Corner Joints (C)

C-U6



A	Permitted welding positions
45°	All positions
20°	Flat and overhead only

Single U-groove weld, welded from both sides.

1. Full strength obtainable for all types of loading.
2. Economical from standpoints of ease of welding and welding required when thickness is greater than $\frac{3}{4}''$. However, joint preparation is expensive.
3. To obtain full strength, the root of the first weld should be chipped out to sound metal before depositing the second weld.

FIGURE 19-35 *(cont.)*

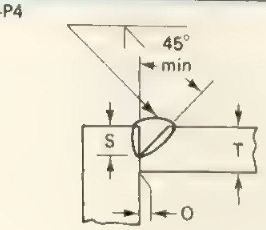
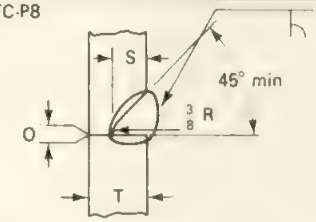
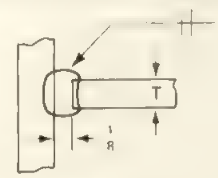
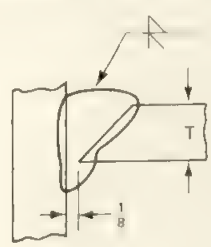
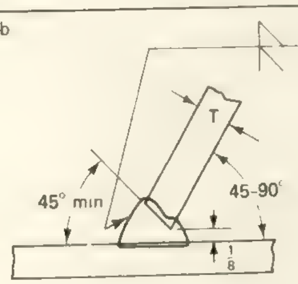
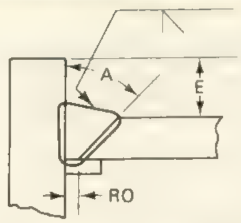
Butt, Tee or Corner Joints (B, T and C)	
BTC-P4  T greater than $\frac{1}{2}$''	Partial penetrating, single bevel groove weld, welded from one side. 1. For T greater than $\frac{1}{2}$ inch. 2. The minimum effective throat thickness shall be T/6 where T is the thickness of the thinner part joined. 3. The effective throat thickness shall be taken as $\frac{1}{4}$ inch less than the depth of groove. 4. May be used for horizontal joints. 5. Should not be used when root of weld is subject to tension bending. 6. Should not be used when subject to impact and/or fatigue loads. 7. Should be used only where design of the structure will resist angular distortion of the joint or where angular distortion is not detrimental.
BTC-P8  T greater than $\frac{1}{2}$''	Partial penetrating, single J-groove weld, welded one side: 1. The minimum effective throat thickness shall be T/6 where "T" is the thickness of the thinner part joined. 2. The effective throat thickness shall be taken as the depth of the groove. 3. May be used in horizontal joints. 4. Expensive joint to prepare. 5. Should not be used when root of weld is subject to tension bending.
Corner and Tee Joints (C and T)	
TC L1  T - $\frac{1}{4}$ max	Square groove weld, welded both sides: 1. Suitable for all types of loading except fatigue loading. 2. Economical in preparation and welding. 3. The root of the first weld should be back gouged to sound metal before depositing the second weld
TC L4a  T = $\frac{3}{4}$'' max.	Single bevel groove weld, welded both sides. 1. Good for most types loading. 2. Economical for thicknesses between $\frac{1}{4}$ and $\frac{3}{4}$ inch from the standpoint of welding required. 3. Shall not be used when tension due to bending is concentrated at the root of weld. 4. Should not be used when subject to fatigue, impact loading, or service at low temperatures. 5 To obtain maximum strength, root of first weld should be gouged to sound metal before depositing second weld. 6. Difficult to obtain sound weld due to perpendicular groove face.
TC-L4b 	Single bevel groove weld, welded both sides, with skewed angle not less than 45°: 1. Good for most types loading. 2. Economical for thicknesses between $\frac{1}{4}$ and $\frac{3}{4}$ inch from the standpoint of welding required. 3. Shall not be used when tension due to bending is concentrated at the root of weld. 4. Should not be used when subject to fatigue, impact loading, or service at low temperatures. 5. To obtain maximum strength, root of first weld should be gouged to sound metal before depositing second weld. 6. Difficult to obtain sound weld due to perpendicular groove face.

FIGURE 19-35 *(cont.)*

Corner and Tee Joints (C and T)

TC U4

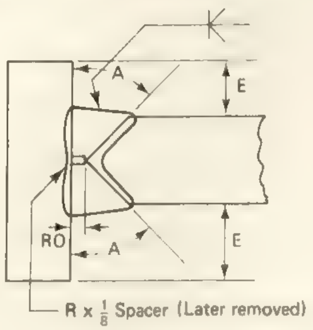


A	RO	Permitted welding positions	E
45°	1/4	All positions	Unlimited
30°	3/8	Flat and overhead only	Not over 3"

Single bevel-groove weld, welded from one side with back-up strip:

1. Should only be used when back side of joint is inaccessible for welding.
2. For use in corner joint, bevel may be designed to the inside of the joint to facilitate welding, if required.
3. Approximately minimum base metal thickness $\frac{5}{8}$ inch.
4. Economical from a standpoint of welding required when the depth of chamfering on each side exceeds $\frac{3}{4}$ inch. Joint preparation is expensive.
5. For additional strength and stress distribution fillet welds can be added.
6. E is the distance the structural member forming the perpendicular face of the groove may extend beyond the weld face of a 30° groove.

TC-U5a

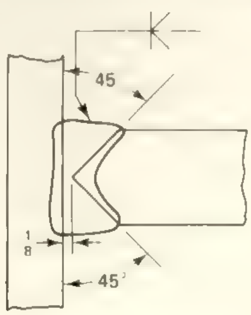


A	R	Permitted welding positions	E
45°	1/4	All positions	Unlimited
30°	3/8	Flat and overhead only	Not over 3"

Double bevel groove weld with spacer:

1. To obtain full strength the root of the first weld should be chipped out to sound metal before depositing the second weld.
2. Difficult to obtain sound weld due to perpendicular groove face.
3. Approximately minimum base metal thickness $\frac{5}{8}$ inch.
4. Economical from a standpoint of welding required when the depth of chamfering on each side exceeds $\frac{3}{4}$ inch. Joint preparation is expensive.
5. For additional strength and stress distribution fillet welds can be added.
6. E is the distance the structural member forming the perpendicular face of the groove may extend beyond the weld face of a 30° groove.

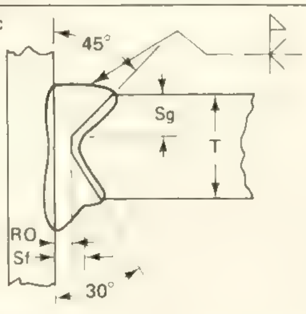
TC U5b



Double bevel groove weld:

1. To obtain full strength the root of the first weld should be chipped out to sound metal before depositing the second weld.
2. Difficult to obtain sound weld due to perpendicular groove face.
3. Approximately minimum base metal thickness $\frac{5}{8}$ inch.
4. Economical from a standpoint of welding required when the depth of chamfering on each side exceeds $\frac{3}{4}$ inch. Joint preparation is expensive.
5. For additional strength and stress distribution fillet welds can be added.

TC U5c



Sf = 3/8
T = 1 3/4 min.
Sg = T/3 Approx.

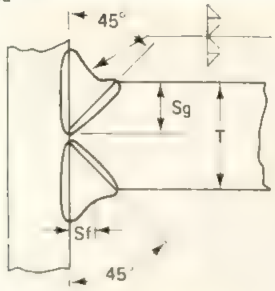
Double bevel weld, single fillet reinforcement:

1. To obtain full strength the root of the first weld should be chipped out to sound metal before depositing the second weld.
2. Difficult to obtain sound weld due to perpendicular groove face.
3. Joint preparation is expensive.
4. When root gouging is required, the 45° bevel shall be designed to the side of the joint that provides the most accessibility.

FIGURE 19-35 *(cont.)*

Corner and Tee Joints (C and T)

TC-P5a

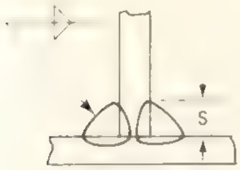


Sf = 5/8 max.
Sg = 3/4 min

Double bevel weld, double fillet weld reinforcement:

1. Effective throat thickness of bevel equals 85% T.
2. Efficiency determined by weld size.
3. Shall not be used when subject to extreme impact and/or high fatigue loads transverse to the axis of the weld joint.

TC-P5b

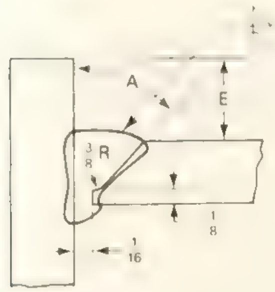


S = 5/8 max.

Double fillet welded tee joint:

1. Efficiency determined by weld size.
2. When greater strength is required, a beveled joint should be used.
3. Shall not be used when subject to impact and/or fatigue loads when the direction of loading is other than parallel to the axis of the weld.
4. Single fillet weld may be used when root of weld will not be subject to tension bending.

TC-U8a

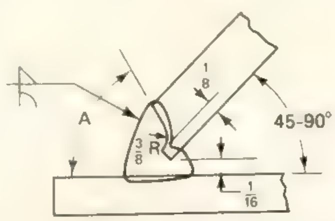


A	Permitted welding positions	E
45°	All positions	Unlimited
30°	Flat and overhead only	Not over 3"

Single J-groove weld, welded from both sides:

1. E is the distance that the structural member forming the perpendicular side of the groove may extend beyond the face of the weld with a 30° groove angle.
2. Full strength is obtainable if the root of the first weld is chipped out to sound metal before depositing the second weld.
3. Difficult to obtain a sound weld due to the perpendicular groove face.
4. Expensive to prepare, however, it becomes more economical from a welding standpoint when the thickness exceeds $\frac{3}{4}$ inch.
5. For additional strength and stress distribution, fillet welds can be added.

TC-U8b



A	Permitted welding positions
45°	All positions
30°	Flat and overhead only

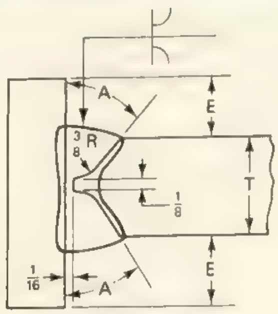
Single J-groove weld, welded from both sides with skewed angle not less than 45°:

1. Full strength is obtainable if the root of the first weld is chipped out to sound metal before depositing the second weld.
2. Difficult to obtain a sound weld due to the perpendicular groove face.
3. Expensive to prepare, however, it becomes more economical from a welding standpoint when the thickness exceeds $\frac{3}{4}$ inch.
4. For additional strength and stress distribution, fillet welds can be added.

FIGURE 19-35 *(cont.)*

Corner and TEE Joints (C and T)

TC U9



Approx. min. T = $\frac{5}{8}''$

A	Permitted welding positions	E
45°	All positions	Unlimited
30°	Flat and overhead only	Not over 3″

Double J-Groove Weld

1. E is the distance that the structural member forming the perpendicular side of the groove may extend beyond the face of the weld with a 30° groove angle.
2. Full strength is obtainable if the root of the first weld is chipped out to sound metal before depositing the second weld.
3. Difficult to obtain a sound weld due to the perpendicular groove face.
4. Expensive to prepare, however, it becomes more economical from a welding standpoint when the thickness exceeds $\frac{3}{4}$ inch.
5. For additional strength and stress distribution, fillet welds can be added.
6. The base metal thickness should be limited to the approximate minimum value of $\frac{5}{8}$ inch.

FIGURE 19-35 *(cont.)*

19-5 INFLUENCE OF SPECIFICATIONS ON DESIGN

All codes and specifications that apply to weldments include design information. In some cases detailed information is presented that must be followed by the designer to meet the code or specifications requirements. These include overall general design guidelines, minimum thicknesses of particular materials, minimum weld sizes, and so on. The different specifications have been mentioned several places in this book; however, the most complete listing of codes and specifications and the types of products they cover are given in Section 21-2. Please refer to this section for the type of products involved. This provides the particular code or specification name and the organization that issues it.

The designer is responsible for obtaining and studying the correct edition of the specifications covering the product being designed. The code rules and conditions must apply.

Information in this chapter cannot be a substitute for the specifications involved. However, when no code or specification applies, the following 20 guidelines will provide information that the designer should follow.

Twenty Welding Joint Design Guidelines

Many products are not covered by codes or specifications. For guidance, designers should consult specifications or codes covering products similar to those being designed. When designers are not governed by a specific code or specification the following twenty welding joint design guidelines may be used.

For mild and low-alloy steel fabrication the following must apply (when codes or specifications do not apply).

1. *Designed strength.* Each weld joint shall be designed or selected to meet the strength requirements for the intended application. Consideration should be given to stress concentrations due to abrupt changes in section, especially when impact, fatigue loads, or low-temperature service is involved.
2. *Standardized joints.* Use the standard welding joints shown by Figure 19-35. These have been designed to require the least amount of weld metal. The design of additional joints not covered should be designed on the same basis.
3. *Complete penetration joints.* Highest efficiencies for all types of loadings result from joints designed for full penetration. Joints requiring the highest efficiency must specify CP in the tail of the weld symbol. For welds made from both sides the designation CP in the tail of the weld symbol means that the back side of the joint should be gouged out to sound metal before depositing the backing weld. Bevel joints welded from one side to a backing strip with the specified root opening should be full-penetraion welds, even though CP is not specified.
4. *Joint preparation time.* Weld joints should be selected or designed to require the least amount of edge preparation with respect to the welding time

required to fill the joint. It is generally less expensive to bevel and weld thinner plates from one side; however, for thicker plate it is less time consuming to bevel and weld from both sides. When comparing fillet welds to groove welds, the effective throat of a fillet weld is less than three-fourths the weld size, while that of the groove weld is normally equal to the weld size.

5. *J- and U-groove preparation.* J and U grooves shall be used only on parts that are readily prepared by machining. In general, machining is more expensive than flame cutting.
6. *Reduce overwelding.* Overwelding increases welding costs and causes extra distortion. Joints designed for 100% efficiency may be subjected to all types of loadings; however, when stiffness is the principal requirement, joints with efficiencies as low as 50% may be satisfactory.
7. *Fillet weld size.* The designed size might be smaller than shown but for general appearance and for fabricating reasons, the minimum fillet weld size to be used on a given thickness of plate for T joints is as follows (the design size might be larger in some cases):

Thickness of Thinner Plate (in.)	Minimum Fillet Weld Size (in.)
Up to ¼ incl.	⅛
[illegible] ¾ incl.	¼
[illegible] 1¼ incl.	½
[illegible] 2 incl.	½
2[illegible] to 4 incl.	¾

8. *Intermittent fillet welds.* Intermittent fillet welds should only be used for strength when the smallest fillet sizes, as given in 7 above, are too large for continuous welds. Exceptions are metallurgical or warpage reasons. Intermittent welds should be used whenever possible on sheet metal and structural parts when stiffness is their prime purpose.
9. *Length of intermittent fillet welds.* For material ¼ in. thick and greater, the minimum length of intermittent fillet welds should be 8 times their nominal size, but not less than 2 in.; the maximum length should be 16 times their nominal size, but not more than 6 in.
10. *Pitch of intermittent fillet welds.* For material ¼ in. thick and greater, the maximum center to center dimension should be 32 times the thickness of the thinner plate, but in no case should the clear spacing between intermittent fillets be greater than 12 in.
11. *Reduce welds.* Eliminate a weld joint by making simple bends wherever possible.
12. *Butt joints.* For butt joints of unequal thickness, smooth the transition by removing metal rather than by adding weld metal.
13. *Double tee joints.* Avoid double-T or cruciform joints whenever possible. Such joints have maximum locked-up stresses.
14. *Corner joints.* For corner joints when bevels are used, prepare the thinner member whenever possible.
15. *Plug and slot welds.* Plug or slot welds, or fillet welds in holes or slots, should not be used in highly stressed members unless absolutely necessary. They should be used where subjected principally to shearing stresses or where needed to prevent buckling of lapped parts.
16. *Groove weld preparation.* Whenever possible, require only one member of a joint to have bevel joint preparation.
17. *Welding position.* Weldments should be designed so that the position in which the welds are made should have the following order of preference:
    (a) Fillet welds, flat, horizontal fillet, horizontal, vertical, overhead
    (b) Groove welds, flat, vertical, horizontal, overhead
18. *Enclosed welding.* Whenever welding is required in enclosed areas or pockets, the enclosed area must contain sufficient openings for access and ventilation for the welder.
19. *Accessibility.* All joints should be located so that the welder will have sufficient room to weld, gouge, peen, and clean slag. There should be no obstructions which prevent the welder from seeing to the root of the joint.
20. *Weld symbols.* All weld joints should be specified by weld symbols. Symbols should be conspicuously placed on all drawings and should refer to views that show the most joint detail, which is normally the profile view.

19-6 DESIGN CONVERSION TO WELDMENTS

The redesign from other manufacturing methods to weldments is being done for many different reasons. These reasons can be classified into the following categories:

- ☐ Economics or reduced cost
- ☐ Quality improvement
- ☐ Appearance improvement
- ☐ Design or product improvement
- ☐ Easier to machine
- ☐ Reduced production cycle time
- ☐ Environmental and other reasons

An investigation into these reasons for redesign soon shows the basic facts that are involved. By taking each of the reasons above and investigating them, we are able to establish the following factors which should assist in making a decision to redesign the present part or structure to a weldment. The economic or *cost reduction* reasons consist of at least the following.

Hundreds of cost studies show that weldments are less expensive than the previously used steel casting. When the weldment is not able to be produced at a lower cost, the design of the weldment should be reviewed. One of the primary cost reduction reasons is the ability to make the product lighter. This occurs since the metal thickness of castings is often thicker than the stresses require but is needed to assist metal flow in the mold. Those parts with excessive thickness due to the metal casting flow requirements are obviously wasteful and would be reduced in the weldment. Often extremely generous radiuses are provided at intersecting planes to assist in metal flow during the casting process. Many surfaces are made extra thick to allow for machining and the machining allowance may be oversize to allow for potential warpage, pattern shifts, and so on. The lap joint used for riveting is also excess metal which can be eliminated with the welding operation. This applies not only to structural work but to tanks and vessels of all types. Weight can be reduced. This reduces the initial cost of the weldment because less metal is involved. This also reduces other charges, for example, shipping charges of the finished product. Reducing the weight allows for more payload in many types of structures.

A machining cost problem that plagues many users of cast parts is the detection of internal defects in the casting after it has been partially or completely machined. Sometimes these castings can be salvaged by welding, many times they must be scrapped with the consequent loss of the time spent machining them prior to finding the defect. Another important cost factor is that weldments frequently simplify and streamline production flow of manufactured parts. Many companies acquire their castings from outside sources. An abnormally long time is usually required to place the order and get the casting produced and received. This cycle time can be greatly reduced by having an in-plant welding department. In comparing the cost of a foundry and cost of a welding shop and metal-preparation shop, studies show that the capital investment to produce the same quantity of product is much lower for the weldment than the casting. The direct labor required to produce the same part in the foundry is usually higher. Many structures made of castings are of such size that the castings must be connected together. These require machined surfaces and bolt holes for fitted bolts. Providing for this extra machining can run up the cost of the final product. Many foundries do not want short-run jobs. Many foundries also do not have their own pattern shops and this adds more cycle time whenever changes are involved or patterns need to be repaired. Pattern damage and damage to core boxes are relatively common for larger castings and these items are expensive to maintain and repair. Many foundries are discontinuing business due to the air pollution problems associated with older iron foundries.

The *quality* of castings is another reason why many companies are making a change from castings to weldments. It was mentioned above that considerable machining may be performed on a casting before it is found to be defective. There are many casting designs that are extremely difficult to manufacture from the foundry's point of view, and these usually contribute to high casting costs. The difficulty in casting certain designs creates a high scrappage rate in the foundry and consequently higher selling prices to the user.

Riveted joints in tanks and vessels, especially those subjected to heating and cooling, will in time become loose and will leak. Riveted vessels often have corrosion problems at the edges and at riveted joints. These problems have been overcome by replacing machined surfaces and gaskets using bolted joints with welded joints. An example of this is the hermetically sealed compressor case for refrigeration equipment. Mechanical fasteners often contribute to other problems such as leaks of threaded screw joints in piping systems. In large structures in which castings and structural members are riveted together the joints become loose and start to flex. In time the rivets shear, the holes elongate, and the working stresses cause the parts to fail. The service problems of composite structures are the reason why they are being changed to weldments. The frames of large coal stripping power shovels were changed from composite structures to weldments. Figure 19-36 is the composite design, and Figure 19-37 is the welded design of a lower frame. The welded frame has proved to be far superior in service. In addition, it is less expensive and lighter

Design improvement is another reason for redesign. This can be not only for more reliability, reduced cost, etc., but also for several other reasons. One of the most important is the design freedom that welding provides the designer. Changes in the ultimate product are relatively easy to make if it is designed of weldments. Design changes are more often required in low-volume production equipment than in mass-produced items. On some types of machinery the production volume is low and pattern costs are absorbed by only a limited number of pieces and thus become an excessive cost. Changes on patterns are very expensive. Another reason for changing is to design the product to reduce space requirements. Weldments can be designed to be more compact than castings. This is particularly important in the transportation industry, especially in aircraft. Another design improvement is the ability for composite weldment construction. Composite construction is a weldment produced by joining steel castings, hot-rolled plate, roll-

FIGURE 19-36 **Riveted lower frame for large stripping shovel.**

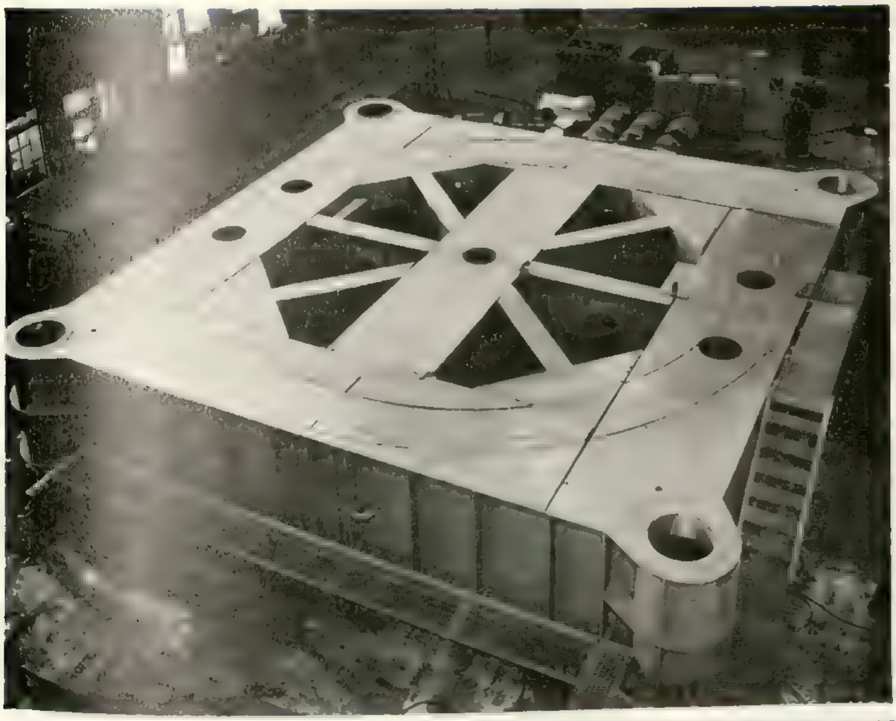


FIGURE 19-37 **Welded lower frame for large stripping shovel.**

ed shapes, stamped items, forged, and formed pieces. Composite construction can also involve the welding together of parts of different types of steel. The type of metal may be placed at a specific spot to provide the necessary strength, corrosion resistance, abrasion resistance, and so on, whereas a casting or forging must be completely of the same material. Design improvement can also be made with regard to deflection resistance or stiffness and vibration control. In general, since the modulus of elasticity of steel is at least double that of cast iron, the weight of items of similar stiffness can be reduced.

Improved appearance is a reason for redesign. This is very similar to design improvement, but can be con-

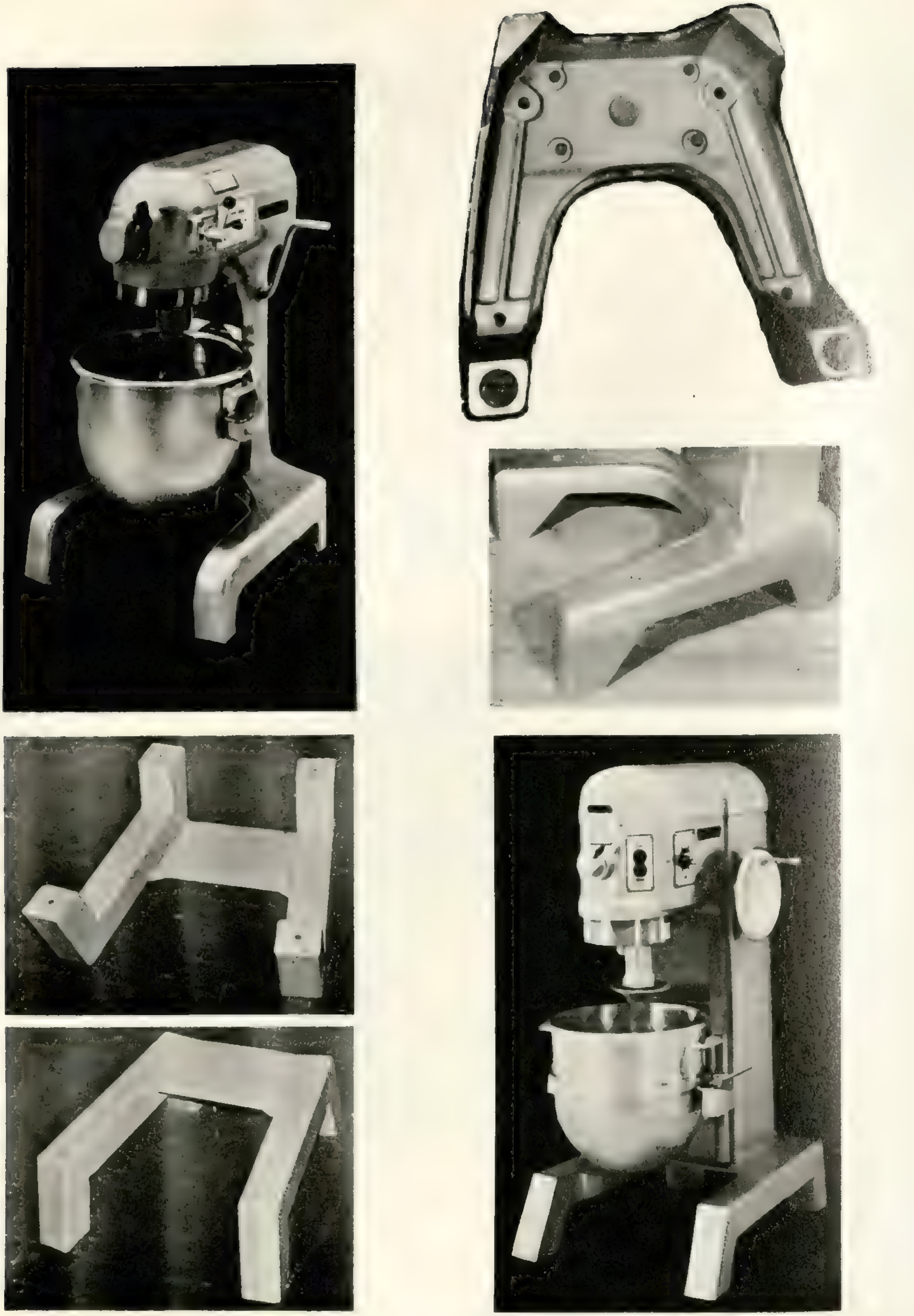


FIGURE 19-38 Cast and welded food machinery base, top and bottom views.

sidered as styling, which is becoming increasingly important for industrial machinery as well as for consumer products. Weldments have cleaner, crisper lines than castings. Figure 19-38 illustrates this point. It shows the top and bottom view of a cast food machinery base and the part redesigned as a weldment. The weldment utilized square mechanical tubing and thin plate. The cost was reduced and cycle time improved. A casting gives an appearance of an old-fashioned design and thus detracts from its appeal to the buyer. Weldments eliminate the cracks and crevices in riveted and bolted construction, and also eliminate the problem of rivets, rivet heads, and so on. The surface of hot-rolled steel is vastly superior to that of cast steel or cast iron and allows reduced finishing costs. Cold-rolled steel is easy to plate with a minimum amount of finishing and polishing. It is sometimes difficult to get a cast surface free enough of porosity to meet sanitation standards. The welds when made with semiautomatic or automatic equipment have a smooth appearance and a surface that can be painted with little or no finishing.

Another reason for the change to a weldment has to do with manufacturing or machining requirements. Machining a large casting requires large machine tools that are extremely expensive. In many cases small castings can be incorporated into composite design weldments. The small castings can be premachined on smaller machine tools. By proper fixturing and using balanced procedures the parts can be incorporated into weldments with minimum warpage, which will eliminate much of the machining requiring large machine tools. The use of small castings eliminates much of the foundry quality problems since they have simpler design and are easier to produce. Scrappage rates and machining time are reduced.

An important factor that enters into this picture has to do with maintenance or rebuilding of equipment. In repair work parts must often be replaced. If they are castings which are no longer available or require excessive procurement time it is wise to redesign the part as a weldment. The weldment can be made immediately and machined so that the equipment can be returned to service more quickly. In preparing welded steel versus cast iron parts the ease of weld repair of the steel is much greater than the repair by welding of cast iron parts. Another reason to use welded steel is the fact that cast iron parts may without warning suddenly fail in a brittle manner. This rarely occurs with welded steel structures.

A cost-savings reason for redesign is the reduced cycle time required by the weldment versus other methods of manufacture. This has been mentioned previously, but it is an important cost factor in manufacturing. It is extremely important in the maintenance of equipment and machinery. An effective way for a company to reduce costs is to reduce the cycle time from start to finish of the manufactured product. With an in-house welding shop and an in-house parts preparation department, this is obtainable. Reduced cycle time is also important for companies supplying spare parts for existing machinery. Most often when a spare part is ordered the user is experiencing an emergency and needs assistance to return to production as quickly as possible. If the extra time required by the foundry is included the time to supply the spare part becomes excessive and the user may decide to fabricate the part.

There are a few other factors that may be the reason for redesign. One of these has to do with the environmental pollution problems experienced by foundries. Older foundries when faced with the expense of installing pollution control devices may decide to discontinue business. When this happens to a foundry supplying you with castings, you may suddenly find the patterns delivered to your door rather than the castings. Redesigns made under these conditions may not be the best.

A new problem sometimes experienced in structural shops is the fact that equipment for riveting may have been discarded. Rivet heaters and rivet squeezers or guns may have been scrapped as a result of lack of use. If a riveted design structure is required, a quick redesign may be in order. It appears that as time goes on there are fewer people who have the ability to hot rivet structures, and riveting may become a lost art due to the high noise level and the efforts to reduce high noise levels in plants.

These are valid reasons for changing to weldments from other types of construction. If you make an analysis of some of the castings or riveted or other mechanically fastened products in your plant, you might find that some of these reasons apply and that you can reap some of the economic advantages by making the change.

Redesign to a Weldment

There are three basic methods for converting from the existing design to a weldment. These are known as (1) direct copy redesign, (2) redesign from the existing part, and (3) new design based on loads and stresses. The optimum economic advantage is obtained when the part is designed from the beginning as a weldment based on the loads and stresses applied to it. The second best method, from an economic point of view, would be the redesign based on the existing part. The quickest method, but the least economical, is to copy the existing part as the new weldment. The latter two methods will be discussed briefly.

Direct Copy

A direct copy of an existing part to a weldment is not the recommended design technique to use if you expect to make the maximum cost reduction. Direct copy redesign is done quickly, usually when time is not available for a complete study. The following is a review of how direct copy redesigns can be done.

Storage tanks, vessels, and similar items can be very easily redesigned as a direct copy of an existing structure. Usually, the lap joints required for the riveted design are eliminated and butt joints for welding are substituted. In this case, the full strength of the metal should be utilized. This means a weld joint having full penetration should be used. The direct copy redesign will produce a stronger tank as well as a leakproof tank. It will be stronger unless the thickness of the metal is reduced. An analysis should be made before reducing metal thickness. If the thickness can be safely reduced it should be done by compensating for the areas used for the rivet holes. This can be done by determining the vertical percentage of the area through the metal and rivet holes compared to the area through the metal alone. The rivet holes can reduce this area by as much as 25%. One-half of this percentage can be used to reduce the thickness of the plate. If the plates become too thin corrosion or pitting may be the controlling factor. Before reducing the plate thickness a thorough analysis should be made by a qualified designer.

Piping work can also be redesigned by the direct copy method. This is simply a matter of eliminating screw-threaded joints and substituting welded joints or welding fittings. If the same size and wall thickness of pipe are used the welded design will have a higher safety factor than the screw-threaded design. This is because of the material cut away when making the threads on the pipe. The pipe wall thickness or schedule should not be reduced to the thickness at the thinnest point, which is at the root of the threads. This could shorten the life of the piping system as a result of corrosion, erosion, and so on.

If wall thickness is reduced it should be done by a qualified designer after reviewing the entire design. A conservative way would be to reduce wall thickness by one schedule rather than attempting to provide a wall thickness equal to the thickness at the root of the thread. In any event, a leakproof system will result which will be superior to the threaded system.

In structural work the direct copy conversion can be used for certain types of structures. Riveted roof trusses, for example, can be changed to a welded roof truss merely by eliminating the rivets in certain of the members, and replacing them with plug welds. The number of holes required would be cut in half. However, the section sizes would remain the same and gusset plates, spacers, and so on, would still be required. Another way for the direct copy method would be to eliminate all holes and use fillet welds at the toes and heels of angles to join the members to gusset plates rather than using plug welds. The equivalent length of weld to provide the same strength as rivets is shown in Figure 19-39. The direct copy method can be used for many other similar type structures as well.

Castings can be redesigned as weldments utilizing the direct copy method. However, to make these conversions intelligently it is necessary to consider the metal from which the casting is made. In the case of redesigning a cast iron part, the section thicknesses can be reduced by one-half and still produce a weldment stronger than the replaced cast iron part. This is because the strength of the steel is at least twice as great as the strength of the cast iron. The stiffness of the steel part will be as stiff as the cast iron part even though the section thicknesses are reduced by one half. Stiffness is related to deflection and the deflection formulas involve the modulus of elasticity of the material. If all other factors are equal, the deflection of the steel part would be only one-half the deflection of the cast iron part. This is because the modulus of elasticity in steel is approximately twice that of cast iron. Therefore, by reducing the section thickness by one-half, the deflection of the redesigned part and the original part will be the same. There is sometimes the question of vibration of a steel weldment versus a cast iron part. The damping capacity of steel and cast iron are about the same. In steel plate construction, the design should be such that the natural frequencies that might occur are outside of the operating range. This is a complex problem and should be placed in the hands of an experienced designer.

In the case of redesigning steel castings to steel weldments, the dimensions of the sections should be left roughly the same. It is difficult to determine when sections of the steel casting are heavier than they need to be unless the design history for the casting is known. Since this is normally not known, it is wise to make the sections of the same thickness. The welds that are taking the full load should be designed for complete penetration. Various gussets and large radiuses can often be eliminated or reduced without affecting the service capabilities of the weldment.

Aluminum sand castings are also sometimes

Rivet Diameter inch	Rivet Shear Value at 15,000 psi Shear Stress	Equivalent Length of Fillet Weld Based on 19,000 psi Deposit—in inches		
		1/4 Fillet	3/8 Fillet	1/2 Fillet
1/2	2950 lb	1	5/8	1/2
5/8	4600 lb	1-3/8	1	3/4
3/4	6630 lb	2	1-3/8	1
7/8	9020 lb	2-3/4	1-7/8	1-3/8
1	11780 lb	3-1/2	2-3/8	1-3/4

FIGURE 19-39 Length of fillet weld (AWS E70XX electrode) to replace rivets (ASTM A502-1 rivets). (From Ref. 6.)

FIGURE 19-40 Redesign aluminum casting to steel stampings.

redesigned as weldments. The ratio of strength of steel versus strength of aluminum should be considered. However, there are many different strength levels of aluminum; therefore, it is impossible to provide ratios unless tests are performed. Aluminum castings can often be replaced by steel stampings of fairly thin parts. An example of this type of redesign is shown in Figure 19-40. This is almost a direct copy of the casting although several dimensions are changed. The weldment made of the stampings is about the same weight as the aluminum casting.

Analysis of Part

The redesign by analysis of the existing part to determine its strength is more economically advantageous than the direct copy technique. In this case efforts are made to analyze the part that is being redesigned without actually analyzing the loads and stresses that are imposed on it. In this type of redesign it is usually possible to reduce the size of members or thickness of sections appreciably to reduce the total weight of the weldment versus the part it replaces. An example of the redesign by part analysis would be the redesign of a structural member such as a roof truss. In a roof truss there are certain members subjected to tensile loading and other members subjected to compressive or possibly column loading. In the members loaded in tension the part can be reduced in cross-sectional area by the amount or by the size of the rivet holes that were punched in the member. In other words, the replacement member would have the same strength since its entire cross section would be utilized. In such a substitution it is necessary to utilize standard rolled sections and the section that provides the cross-sectional area equal to that of the original less the rivet hole area should be used. For safety's sake it might be wise to go up one size for the member. This technique must not be used for long members subjected to compressive loads. It cannot be used because such members are designed based on the slenderness ratio and the possibility of buckling rather than the unit stress produced in compression. For those members subjected to bending, particularly outer fibers where the bending load produces tensile stresses, the size of the members should not be reduced; the reason is that the stress is not consistent through the entire length of the member, and the stress level could be extremely low at the joint or where the rivet holes are located. The allowable stresses may be proper at some other point; therefore, this member should not be reduced in size. A designer with experience in this field should be involved.

In the redesign of existing pipe or vessel systems, the remarks made concerning the direct copy method should be considered, but more critically in light of maximum section thickness reduction to achieve maximum savings.

In redesigning castings the previous comments concerning castings should be considered. If it is possible to change the shape to incorporate rolled sections, or to avoid unnecessary bends or curves, those changes should be made while retaining the general shape of the original part. Much experience is required to redesign, using the analysis of the existing structure. The more experience one has had in this work, the more impressive will be the savings that result.

For maximum cost savings, the complete redesign based on the fundamental factors involved should be done. This would mean following the general concepts outlined in the earlier part of this chapter.

19-7 WELDMENT REDESIGN TO REDUCE COST

Value engineering programs generate large cost savings from welded product analysis. Value engineering groups review all practices within a company to find a better way to provide the same value for less cost. The value engineering technique should be used for evaluating welded products and will usually suggest changes that will save money.

Value engineering of welded products may take several paths: Analyze the weldment design, the welding procedure, materials preparation, and the welding operation. Since the design is the basis for the product, it is well to relate all factors to the design except those that must be accomplished by other groups.

The first step is to involve welding shop personnel. Ask them if the weldment is easy to weld. Are there any difficult or inaccessible weld joints? Are welds covered up by parts added later? Do the parts fit together without trimming, or create large gaps? The investigation team should also check other manufacturing personnel and everyone involved in the manufacture of the weldment.

Critical items should be investigated and solutions found. The following items should be checked and corrected.

Designers and Engineers

1. Investigate the field sevice record. If there have been no field failures, recheck the load calculations; perhaps the weldment is overdesigned.
2. Investigate field failure reports. The redesign should correct design weakness.
3. Eliminate weld joints whenever possible. Use rolled sections, use small steel castings for complex areas, and use formed or bent plates.
4. Reduce the cross-sectional area of all welds. Utilize small root openings, small groove angles, double- instead of single-groove welds, and so on. The weld metal is the most expensive metal on the weldment. The amount of weld metal should be kept to a minimum.
5. Utilize fillet welds with caution. If the size is doubled, the strength is doubled but the cross-sectional area and the weight increase four times.
6. Intermittent fillet welds should be studied. It may be possible to reduce the fillet size and make the weld continuous and use less weld metal.
7. Where extra thickness is required, use flame-cut heavy plates or billets or small simple castings.
8. Pre-machine parts wherever possible for bearings, housings, etc. This avoids large machine tools for completed weldments.
9. Provide easy accessibility for all welds. Otherwise, special attention and time are required.
10. Select weldable materials: mild steel and low-alloy steels. Difficult-to-weld metals require preheat and complex expensive procedures.
11. Design the weldment with the least number of thicknesses of steel. This reduces stocking extra thicknesses.
12. Balance using heavier materials without reinforcements against the cost of extra pieces and welding.
13. Use weld symbols with size notations for all welds.

Process or Manufacturing Engineers

1. Written welding procedures or job sheets should be provided to the welding department for all jobs.
2. Use the semiautomatic or automatic or robotic method of application of welding.
3. Use high-deposition-rate welding processes and filler metal.
4. Consider stress relieving. Is it required for service or for machining stability? Can the vibratory technique be used?
5. Provide fixtures when economically possible; use simple fixtures for setup operations.
6. Use subassemblies where possible.
7. Utilize positioning equipment when economies are provided.

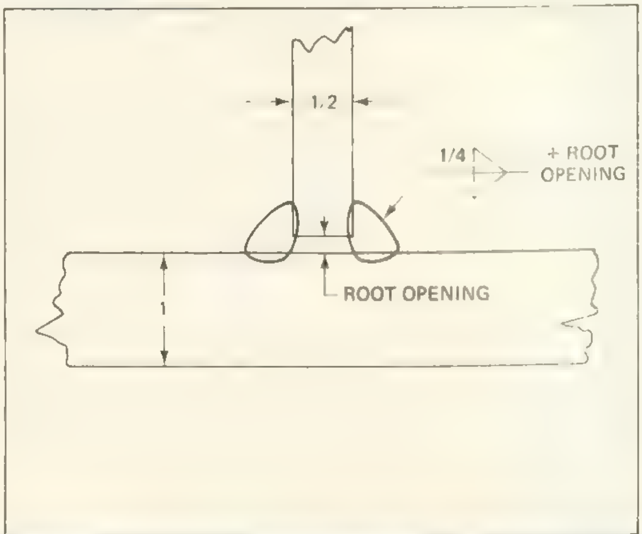
Parts Preparation Personnel

1. Shear or blank parts whenever possible—use automatic back gauges.
2. Use automatic shape-cutting equipment. Use the optimum process or fuel gas.
3. Utilize stops, gauges, and so on, in metal forming operations to increase accuracy of parts.
4. Check with the welding department for fitup problems and fix part drawings.

Welding Department Personnel

1. Provide accurate fitup of all weldments. Use fixtures for setup whenever possible. Tack weld only in weld setup fixtures. Inspect fitup prior to welding. Figure 19-41 shows the effect of fitup on extra weld metal and time required.
2. Do not overweld. Make welds the size shown on weld symbols. Figure 19-42 shows the additional weld metal and time required when overwelding.

FIGURE 19-41 Extra weld metal required for poor fitup.



ROOT OPENING	FILLET SIZE REQUIRED	WELD METAL REQUIRED LB/FT.	% MORE WELD METAL REQUIRED
0	1/4"	0 212	–
1/16"	5/16"	0.334	157%
1/8"	3/8"	0.476	224%
3 16"	7/16"	0.652	308%

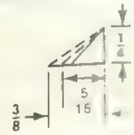
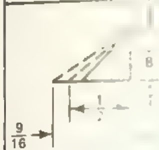
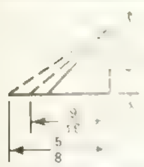
Fillet Size Overwelded Size		Theoretical wt/ft	Overwelding Requires This Much More Weldmetal
	1/4 × 1/4 design 1/4 × 5/16 1/4 × 3/8	0.106 0.133 0.159	– 25% 50%
	5/16 × 5/16 design 5/16 × 3/8 5/16 × 7/16	0.166 0.199 0.232	– 20% 40%
	3/8 × 3/8 design 3/8 × 1/2 3/8 × 9/16	0.239 0.318 0.358	– 33% 50%
	1/2 × 1/2 design 1/2 × 9/16 1/2 × 5/8	0.425 0.477 0.531	– 12% 25%

FIGURE 19-42 Extra weld metal required for overwelded fillets.

3. Eliminate excessive reinforcing on all welds. Reinforcing is not required to obtain weld strength.
4. Utilize subassembies whenever possible. This will minimize distortion and reduce cycle time.
5. Follow welding procedures to minimize distortion. Distortion will create poor fitup, which may require additional welding.
6. Use positioning equipment and flat-position welding in all production.
7. Follow welding procedures. Use proper arc length and welding current.
8. Use all the filler metal purchased. Do not discard long lengths. Use large electrode sizes. Purchase filler metals in large lot sizes.
9. Provide power tools for slag removal and for weld finishing.
10. Provide for welder comfort and safety by using scaffolding, worker positioners, guard rails, and so on.
11. Maintain welding equipment efficiency through routine maintenance procedures.
12. Check for cable and connector efficiency in the welding circuit. Hot spots waste power.

Involvement of all personnel will turn up unexpected cost savings. Be flexible.

Finally, take an overall view of the weldment. The design must be functional and improve it every time it is changed.

19-8 WELDING SYMBOLS

The American Welding Society developed and established a system of welding symbols in the 1930s. The purpose was to identify the location of welds and transmit this information on engineering drawings from the designer to the welding shop. Since that time, numerous revisions have been made. The original purpose is being fulfilled and welding symbols are being used increasingly by progressive fabricators and users of welding. In the recent past, through the efforts of the International Institute of Welding and the International Standards Organization, the welding symbols of different countries are being unified so that there will be a common system of weld symbols throughout the world. The latest edition of the American Welding Society's "Standard Symbols for Welding, Brazing, and Nondestructive Examination"[7] is in substantial agreement with the ISO standards and those of many countries throughout the world. Increased international trade makes the standardization of welding symbols an important objective. For universal international use, two more steps are required. This includes the conversion of the American measuring system to the metric system, and the second is to resolve the differences between drafting-room practices in North America and in Europe. In North America the third-angle projection, and in Europe the first-angle projection, is normally used. In the first-angle projection, the side view is the left-side view, and in the third-angle projection, the side view is the right-side view. This is not too important with respect

to weld symbols but does cause confusion in interpreting drawings and symbols.

The purpose of welding symbols is to describe the desired weld of a weldment accurately and completely. The welding symbol can also be used to transmit other information, such as specifications and procedures. This is done by means of special information in the tail of the arrow. Welding symbols can also be combined with nondestructive examination symbols.

The welding symbol consists of eight elements, which may or may not all be used in each symbol.

1. Reference line
2. Arrow
3. Basic weld symbol
4. Dimension and other data
5. Supplementary symbol
6. Finish symbol
7. Tail
8. Specification, process, or reference

The first and second elements and either the third or seventh must be used to make an intelligible welding symbol. The others may or may not be used, in accordance with the necessity of passing along the information or the standard practice of the organization that is using them.

The foundation for constructing a welding symbol is the reference line. The reference line is always shown in the horizontal position, and it should be drawn near the weld joint that it is to identify. The other parts of the welding symbol are constructed on the reference line. Each of the other elements of the welding symbol must be placed in proper location with respect to the reference line and in accordance with the standard location (Figure 19-43). The elements that describe the basic weld, the dimensions and other data, the supplementary, and the finish symbol are always located with the same relationship to the reference line no matter which end of the reference line carries the arrow.

The next important element of the welding symbol is the arrow. This is a line from one end of the reference line to an arrowhead to the arrow side or arrow side member of the weld joint. When the symbol is used for joints that require the preparation of one member, only the arrowhead should point with a definite break to the member of the joint that is to be prepared.

The other end of the reference line carries the tail of the arrow. The area in the tail can be used to provide references to specifications, processes, or other specific information. When no specification, process, or other information is used, the tail is omitted.

The most important part of the welding symbol is the weld symbol, which is used to indicate the desired type of weld. The basic symbols are shown in Figure 19-44.

If the basic weld symbol is placed under the reference line, that symbol is to define the weld on the arrow side of the joint or the arrow side member of the joint. If the weld symbol is placed above the reference line, it is to define the weld made on the other side or other side member of the joint. When the symbol is placed on both sides, it would indicate that the weld is made on

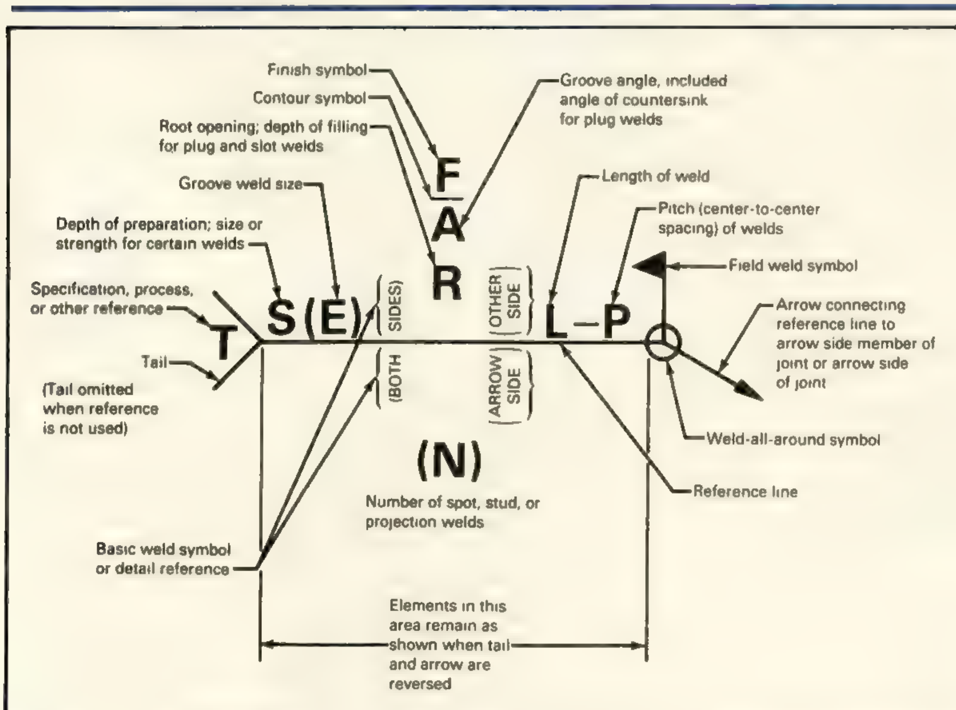


FIGURE 19-43 Standard location of elements of a welding symbol.

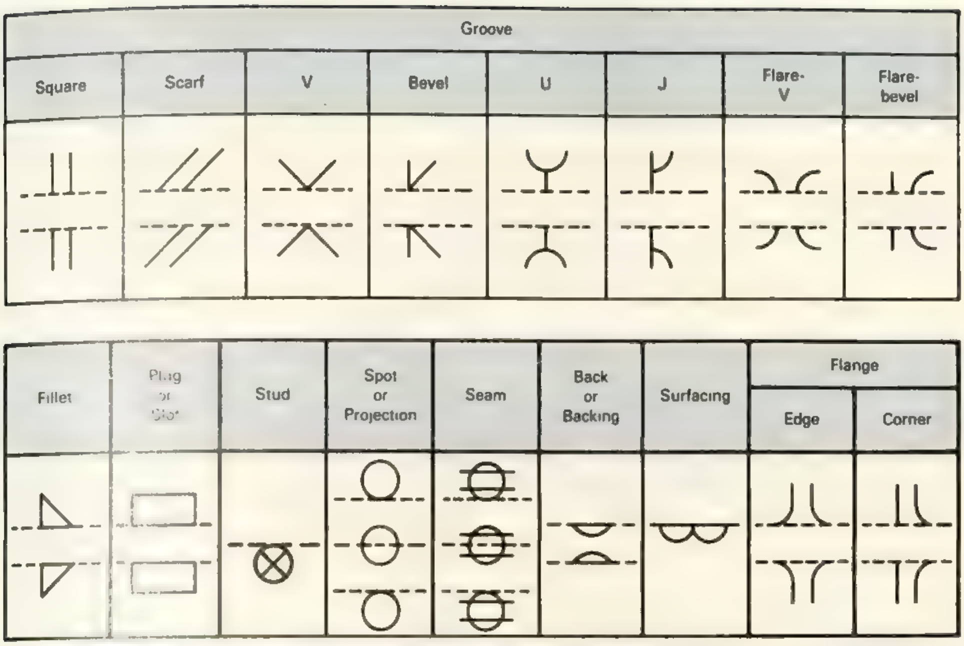


FIGURE 19-44 **Basic weld symbols.**

both sides. Figure 19-45 shows the identification of the arrow side and the other side of the joint and the arrow side and other side member of the joint.

The various dimensions that help describe and define the weld have a specific location relationship to the weld symbol. The size of the weld is to be placed at the left of the weld symbol. In groove welds, if the size is not shown, it indicates complete joint penetration. The root opening or depth of filling for plug and slot welding is to be placed directly in the weld symbol. The groove angle, that is, the included angle, for groove welds and the included angle of countersink for plug welds are placed above or below the weld symbol. This dimension is often omitted if there is a company standard or all-inclusive note on the drawing. To the immediate right of the weld symbol will be the dimension indicating the length of the weld, and if required, a dash and the next number will indicate the pitch, which is the center-to-center spacing of intermittent welds. These are all given by Figure 19-46, showing the standard location of elements of a welding symbol.

More than one basic weld symbol can be used to specify a weld joint. For Example, in a T joint a fillet weld may be included in addition to a groove weld. In

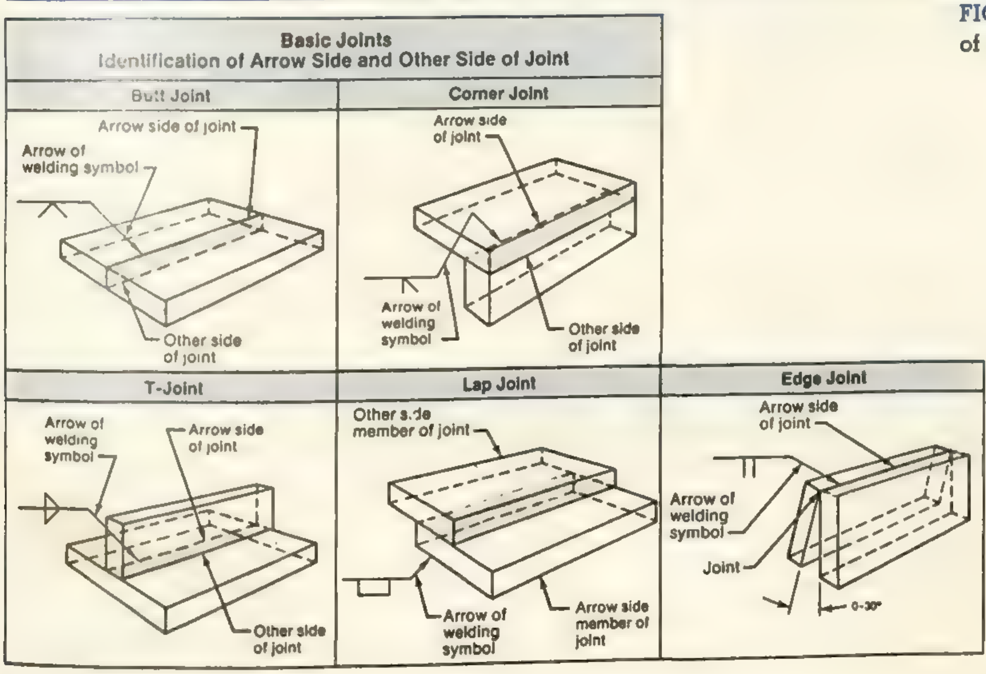


FIGURE 19-45 **Identification of arrow side and other side.**

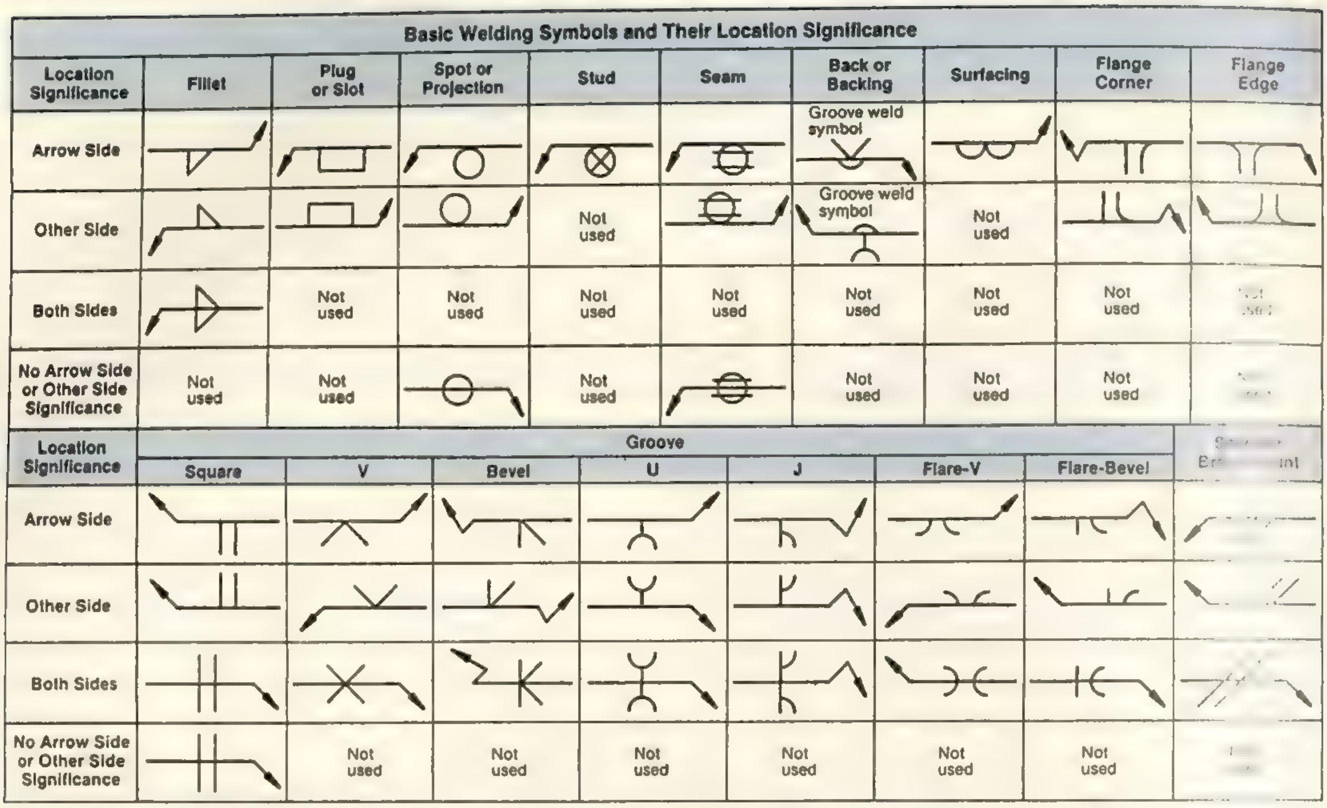


FIGURE 19-46 Basic welding symbols and their location.

this case, the basic groove weld symbol would be made to touch the reference line and the basic fillet weld symbol would be added on top.

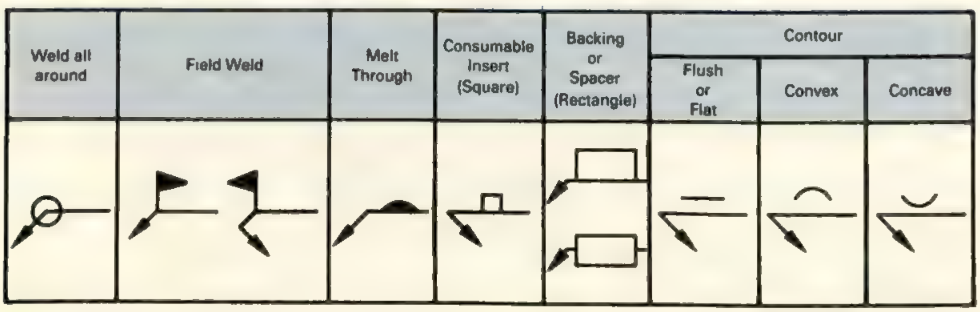
The next element of the welding symbol consists of the supplementary symbols. These are to be used in conjunction with welding symbols and have a specific location. The supplementary symbols are shown in Figure 19-47. The supplementary symbols are used for situations that require them. Supplementary symbols include the weld-all-around symbol, the field weld symbol, symbols indicating the contour of the finished weld, and others. Surface finish symbols are used for very exacting requirements.

The following letters are used to indicate the method of finishing but not the degree of finish.

- ☐ C Chipping
- ☐ G Grinding
- ☐ H Hammering
- ☐ M Machining
- ☐ R Rolling

A number of typical welding symbols are shown in Figure 19-48. Basic weld symbols, as well as the standard location of elements of a welding symbol, should be learned by all who use weld symbols: the designer, the

FIGURE 19-47 Supplementary symbols.



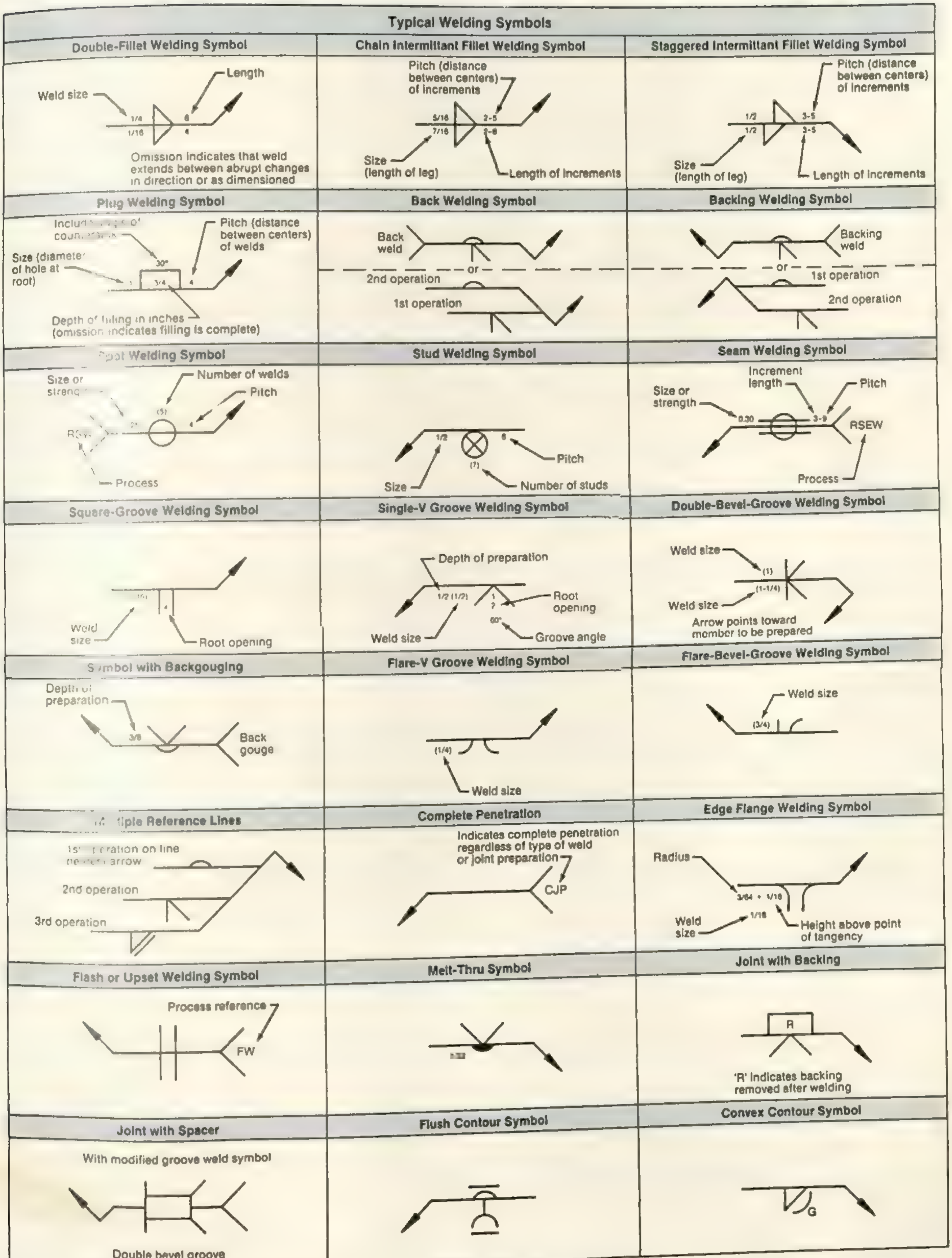


FIGURE 19-48 Typical welding symbols including use of supplementary symbols.

draftsman, the detailer, the layout man, the setup man, the welder, and the welding inspector.

The AWS "Standard Symbols for Welding, Brazing, and Nondestructive Examination" should be available in every drafting room, engineering department, and weld shop. Training programs are available for learning welding symbols.

QUESTIONS

19-1. List all the advantages of welded construction.

19-2. The designer is responsible for weldment design. List the factors that the designer must consider.

19-3. Define and explain the factor of safety.

19-4. Explain tensile loading, compression loading, bending loading, torsion loading, and shear loading.

19-5. What is a stress concentration? What causes it? How can it be eliminated?

19-6. How does a stress concentration affect the life of a weld?

19-7. What are the five basic types of joints? Describe each.

19-8. What are the eight types of welds? Describe or sketch each.

19-9. Define the eight parts of a fillet weld.

19-10. Define the five parts of a groove weld.

19-11. If the fillet weld size is doubled, how much more weld metal is required?

19-12. What are the seven types of groove welds? Are they used as single or double?

19-13. Explain the weld joint identification number system. What is a BTC-P8 joint?

19-14. Name the fields of welding in which weldment design is governed by specifications.

19-15. What is weldment conversion? How is it done?

19-16. Is the welder responsible for not making an inaccessible weld? Why?

19-17. Which is the arrow side of a weld symbol reference line?

19-18. What does the triangle symbol indicate? How do you specify a double one?

19-19. What is the symbol for *weld all around*? What does it mean?

19-20. What symbol indicates welding at field erection? Describe it.

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3. Charles M. Jennings, "Welding Design," *Transactions of the ASME*, Oct. 1936.
4. "Structural Welding Code," AWS D1.1, American Welding Society, Miami, Fla.
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20

Cost of Welding

20-1 WELDMENT COST ELEMENTS

The cost of welding like the cost of any industrial process includes the cost of labor, the cost of materials, and the overhead expense. Welding costs must be accurately determined since they are a part of the total cost of products. Welding costs are used to determine cost estimates for bidding on welding work, for setting rates for incentive programs, and for comparing welded construction and competing processes.

It is necessary to differentiate between the cost of weldments versus the cost of a specific weld. For example, in pipe welding, we are interested in the cost of making each butt weld. This is done in order to determine the cost advantage of one process versus another or between one joint design versus another.

The cost of the weldment is of major importance. This includes the cost of the weld, the cost of the material required, the preparation of the parts, and the postweld treatment required. The cost of the weldment is required to determine the competitive advantage of a weldment versus a casting or some other type of construction.

The costing of welds and weldments must fit into the company's accounting practices. This can be done since all cost systems include labor, material, and overhead. This chapter presents methods which allow

OUTLINE

welds to be costed when using any of the arc welding processes. These methods can be used to determine the cost of competing welding processes. The basis for this system is the amount of weld metal deposited to produce the weld joint. It requires the input of data concerning labor costs related to the time required to accomplish the weld, plus the materials required, plus the overhead involved. Normally, additional overhead such as factory administrative costs and company overall sales and administrative costs are prorated according to direct labor involved in manufacturing the part.

The basis for labor costs is time: time per weld, or time per increment of the length of a weld, or the time required to weld a part. Time is universal and in many situations time represents the cost of the labor. When labor costs are prorated in another fashion this can quickly be related to time per part or parts per unit of time. Welding materials are also related to the total cost. For those processes where weld metal is deposited in the joint, the amount of metal deposited becomes the basis of the calculation of material costs. The amount of metal required is then related to process to determine the amount of filler metal required to accomplish the weld joint. The rate of depositing weld metal relates to time, which is the basis for labor costs.

This same basis can be used for establishing time standards, and for constructing charts of data that can be used for estimating purposes, rate setting purposes, etc.

The welding procedure is the starting point in establishing welding costs. Welding procedure schedules presented throughout this book can all be used in establishing welding costs. To be of value, the welding procedure schedule must include the welding joint details, which in turn establish the amount of weld metal required to accomplish a weld joint. The procedure must also include the welding process and the type of filler metal involved since this relates to the cost of the filler metal. The welding procedure must specify the welding current since welding current, filler metal, and process relate to the rate of depositing weld metal and the utilization of filler metal purchased and deposited in the weld. The welding procedure must include the method of application since this influences the operator factor or duty cycle which in turn determines the amount of labor used in depositing weld metal. Finally, the travel speed should be included in the procedure since it determines the amount of time required to produce weld joints. Travel speed is vitally important when weld metal is not deposited in the joint.

The procedure provides the data needed to calculate the cost of a weld. The labor rate and the cost of filler metals must be included to get actual costs. In this regard, filler metals include fluxes, shielding gases, and any other material consumed in making the weld.

The cost of the weldment includes the cost of welding; however, closely related to the cost of welding is the cost of joint preparation. This is included in total weldment cost since joint preparation is required and it adds to the total weldment cost. Joint preparation varies according to material thickness and joint design. To minimize welding cost it is wise to consider alternate joint designs and alternate welding processes. Less expensive joint preparation, based on joint design, can be used with certain processes; for example, with the electroslag welding process a square cut or a mill edge can be used for the joint preparation. For deep groove welds one or two cuts are required for the submerged arc welding process. The tradeoff involves the amount of weld metal required to produce the joint. In some cases more weld metal might be required but it can be deposited at a higher rate. This might offset a different joint design that uses less weld metal but is applied with a slower process. These factors must all be studied in order that the optimum weld joint can be made for the least cost.

The cost of postweld treatment will be considered but without the same detail. Postweld treatment includes final machining, grinding or polishing, heat treating, shot blasting, and possibly straightening. They are important, since some welding processes require more or less postweld treatment which influences the total cost of the weldment.

Welding, particularly manual welding, is a highly labor intensive manufacturing process. As plants change from manual to semiautomatic, the labor input is reduced, and in changing to automatic it is further reduced. In view of this, calculations for weld costs must be extremely accurate and based on practical procedure data. Comparisons of different welding processes or methods of application can be the basis for investments in automatic equipment. Data in the book and this chapter provide the basis for making these cost determinations, which can greatly affect capital expenditures.

Field welding costs more than shop welding. Welding in the horizontal, vertical, or overhead positions costs more than welding in the flat position. Local working conditions in the shop or on the job affect costs. Available equipment for fitting up or handling the work, experience and skill of the welders, power rates, special code requirements, weather and temperature conditions, industrial regulations, and many other variables exert so much influence on final costs that tables, graphs, charts, and so on, can be offered only as general guide lines applying to average conditions.

The tables and graphs that provide final costs when labor rates are inserted should be used with caution. These data must be based on many assumptions which might not apply in your situation. For example, the weld designs can vary in root opening, groove angle, and so on. The reinforcement may be different. The filler metal yield varies from electrode to electrode and the operator factor can also vary widely. In addition, the data might be

slanted to favor one process over another. The data presented in this chapter will enable you to construct your own tables and charts based on your standard weld designs, the processes you employ, the filler metals used, and the operator factors you expect. When these data are modified by your pay rates, overhead rates and materials prices, they will apply to your operation. It is wise to include only the standard data in charts, since rates and prices continuously change.

20-2 WELD METAL REQUIRED FOR JOINTS

The material cost is based on the amount of weld metal deposited in the joint. The exception is the autogenous welds when weld metal is not deposited. The same method of calculating weld metal in joints can also be used for surfacing and overlay applications. The procedure involved applies to all the arc welding and other welding processes in which metal is deposited.

This system utilizes standardized joint designs. Most welding organizations welding codes and standards provide standardized designs. Standardized designs are also presented in Chapter 19. This same information is presented here with area and weight calculated for these joint designs in various thicknesses of material. This information is based on the use of steel base metal and weld metal. However, the information is presented so that data for other metals can be easily calculated. The cross-sectional area is related to the standard joints and can be modified for different metals based on their density. In this chapter only the conventional measurements are provided since to include metric measurements would unduly complicate the tables.

Every weld has a cross-sectional area which can be determined by straightforward geometric calculations. If weld details are standardized it is a simple matter to calculate the cross-sectional area. The formulas for the different welds are shown in Figure 20-1. In these figures the letter designation for the different parts of the weld are the same as Chapter 19. These are as follows:

- *A* Groove angle
- CSA Cross-sectional area
- *D* Diameter plug weld, arc spot weld
- *L* Length of slot weld
- *R* Radius (used in J and U grooves)
- RF Root face
- RO Root opening
- *S* Fillet size, bead size, or size of groove weld if not complete penetration
- *T* Thickness
- *W* Width of surfacing

In addition, the weld designs are the same as those in Chapter 19.

Information shown in Figure 20-1 can be applied in different ways. For example, the bead weld can be used for a backing bead or a sealing bead or for thinner metals for the flange, edge, and corner weld. The amount of metal required for the bead weld may sometimes be added to the full-penetration groove welds for root reinforcing.

When welds of different design configuration are used, the cross-sectional area is calculated using geometric area formulas. The formulas for each weld provide theoretical cross-sectional area values with a flush surface. Weld reinforcement is not included in these values. For practical purposes, however, reinforcement must be added to a weld. The standardized weld designs are shown in Figure 20-2 (see page 614). In this figure, the different weld designs are related to material thicknesses. The theoretical cross-sectional area in square inches is shown for each weld in its normal range thickness. In addtion, the theoretical weight of the weld deposit is shown related to the design and thickness. The weight is based on 12 in. or 1 ft of joint of steel weld metal in pounds per linear foot of weld. This is calculated using Equation (20-1).

The constant 0.283 is the weight of a cubic inch of steel in pounds per cubic inch. The data can be used for any metal by using its density or weight per cubic inch.

To make this datum more practical a reinforcement factor is added. A value of reinforcement of 10% is added to single groove welds and 20% reinforcement is added to the double groove welds. Ten percent is also added as reinforcement for fillet welds. These are arbitrary figures but they are sufficiently accurate for most calculations. For greater accuracy it may be desirable to make representative welds, cross section them, and measure the reinforcement. This would be accurate for a particular weld, but since reinforcement varies it may not be worth the effort. The amount of reinforcement on a weld must be held to a minimum since it increases the amount of weld metal required. Figure 20-2 therefore includes two additional columns. One provides the cross-sectional area of the welds in square inches in the different material thicknesses with the reinforcement added. The final column provides the weight of the weld deposit with reinforcement in pounds per foot of weld.

Another value of the data presented in Figure 20-2 is their usefulness in visualizing how welding costs are related to weld designs. They illustrate the amount of weld metal required for different weld designs. For example, they will show the increase in cross-sectional area or

$$\text{weight of deposit (lb/ft)} = \text{cross-sectional area (in.}^2) \times 0.283\ (\text{lb/in.}^3) \times 12 = 3.396 \qquad (20\text{-}1)$$

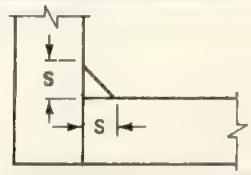
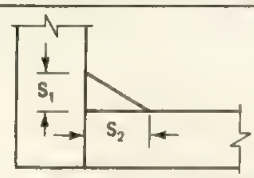
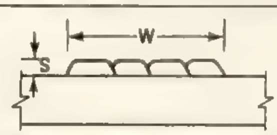
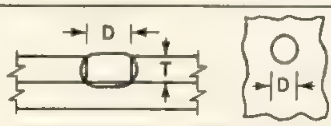
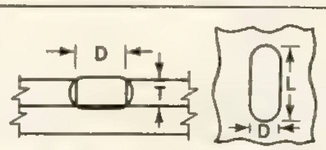
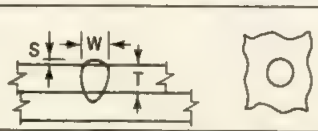
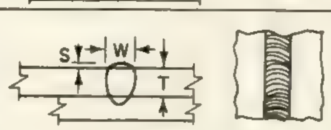
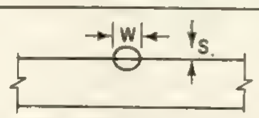
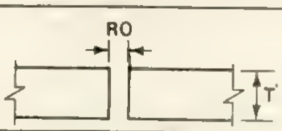
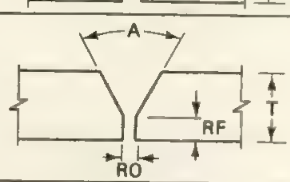
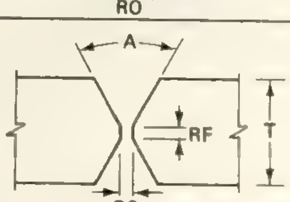
WELD	DESIGN	FORMULA FOR CROSS SECTION AREA
FILLET (EQUAL LEGS)		CSA = $1/2(S)^2$
FILLET (UNEQUAL LEGS)		CSA = $1/2\ (S_1 \times S_2)$
SURFACE		CSA = S x W
PLUG		VOL = $\pi\left(\frac{D}{2}\right)^2 \times T$ FORMULA PROVIDES VOLUME OF WELD METAL PER WELD
SLOT		VOL = $\left[\pi\left(\frac{D}{2}\right)^2 + (L - D)D\right]T$ FORMULA PROVIDES VOLUME OF WELD METAL PER WELD
ARC SPOT		VOL = $1/2S\left(\pi\frac{W}{2}\right)^2$ (VOLUME PER WELD) FORMULA PROVIDES VOLUME OF WELD METAL PER WELD
ARC SEAM		CSA = 1/2WS
BEAD		CSA = 1/2WS
SQUARE		CSA = RO x T
SINGLE V		CSA = $(T - RF)^2 \tan\left(\frac{A}{2}\right) + RO \times T$
DOUBLE V		CSA = $1/2(T - RF)^2 \tan\left(\frac{A}{2}\right) + RO \times T$

FIGURE 20-1 Cross-sectional area of welds.

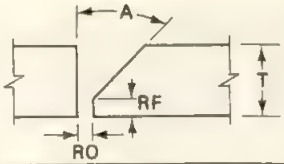
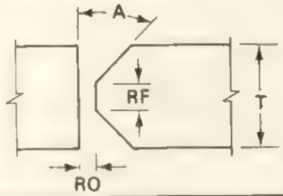
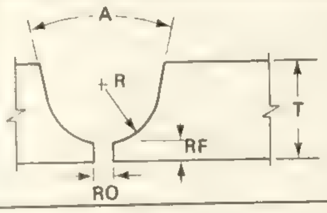
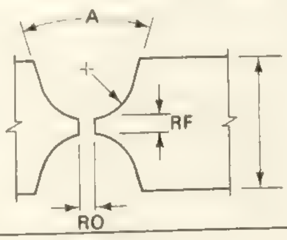
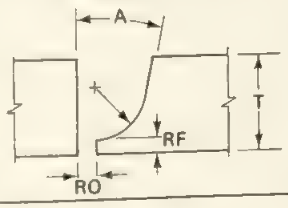
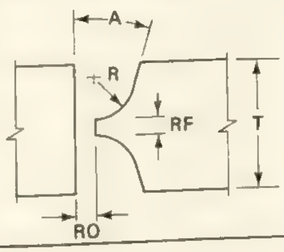
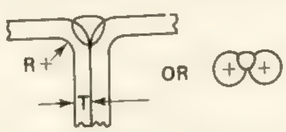
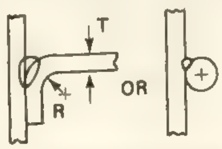
WELD	DESIGN	FORMULA FOR CROSS SECTION AREA
SINGLE BEVEL		$CSA = 1/2(T - RF)^2 \tan A + RO \times T$
DOUBLE BEVEL		$CSA = 1/4(T - RF)^2 \tan A + RO \times T$
SINGLE U		$CSA = (T - R - RF)^2 \tan\left(\frac{A}{2}\right) + 2R(T - R - RF) + 1/2\pi R^2 + RO \times T$
DOUBLE U		$CSA = 1/2(T - 2R - RF)^2 \tan\left(\frac{A}{2}\right) + 2R(T - 2R - RF) + \pi R^2 + RO \times T$
SINGLE J		$CSA = 1/2(T - R - RF)^2 \tan A + R(T - R - RF) + 1/4\pi R^2 + RO \times T$
DOUBLE J		$CSA = 1/4(T - 2R - RF)^2 \tan A + R(T - 2R - RF) + 1/2\pi R^2 + RO \times T$
FLARE V		$CSA = \frac{(2 \times R + T)^2 - \pi(R + T)^2}{2}$
FLARE BEVEL		$CSA = \frac{(2 \times R + T)^2 - \pi(R + T)^2}{4}$

FIGURE 20-1 *(cont.)*

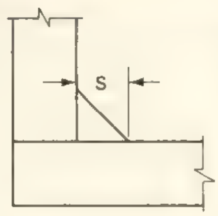
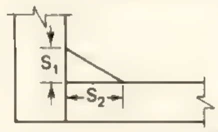
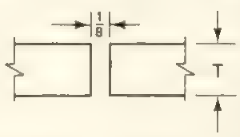
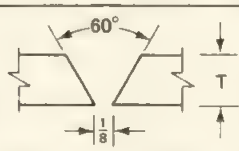
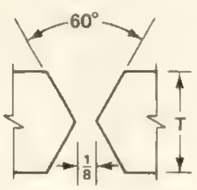
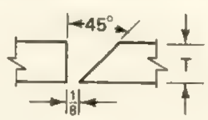
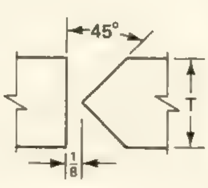
Weld	Design	T in inch	CSA Theor. in.^{2}	Weld Deposit Theoretical lb/ft	CSA w/ref. in.^{2}	Weld Deposit w/ Reinforcement lb/ft
Fillet (equal legs)		1/8	0.008	0.027	0.009	0.030
		3/16	0.018	0.061	0.020	0.067
		1/4	0.031	0.106	0.034	0.117
		5/16	0.049	0.167	0.054	0.184
		3/8	0.070	0.238	0.077	0.262
		7/16	0.096	0.326	0.106	0.360
		1/2	0.125	0.425	0.138	0.468
		9/16	0.158	0.537	0.174	0.591
		5/8	0.195	0.663	0.215	0.729
		3/4	0.281	0.956	0.309	1.052
		7/8	0.383	1.503	0.421	1.653
		1	0.500	1.700	0.550	1.876
Fillet (unequal legs)		1/4 x 3/8	0.047	0.160	0.052	0.176
		3/8 x 1/2	0.094	0.319	0.103	0.351
		1/2 x 5/8	0.156	0.530	0.172	0.583
		5/8 x 3/4	0.234	0.795	0.258	0.875
		3/4 x 1	0.375	1.274	0.413	1.401
Square		1/8	0.016	0.054	0.019	0.065
		5/32	0.019	0.065	0.023	0.078
		3/16	0.023	0.078	0.027	0.094
		7/32	0.027	0.092	0.032	0.110
		1/4	0.031	0.105	0.037	0.126
		9/32	0.035	0.119	0.042	0.143
		5/16	0.039	0.132	0.047	0.158
Single V		1/4	0.067	0.228	0.074	0.251
		3/8	0.128	0.384	0.141	0.422
		1/2	0.206	0.702	0.227	0.772
		5/8	0.305	1.040	0.336	1.144
		3/4	0.418	1.430	0.460	1.573
		1	0.702	2.395	0.772	2.635
Single bevel		3/4	0.256	0.874	0.307	1.049
		1	0.414	1.420	0.497	1.704
		1-1/4	0.608	2.075	0.730	2.490
		1-1/2	0.838	2.860	1.006	3.432
		1-3/4	1.105	3.765	1.326	4.518
		2	1.405	4.780	1.686	5.736
		2-1/4	1.742	5.945	2.090	7.134
		2-1/2	2.210	7.530	2.652	9.036
		2-3/4	2.530	8.620	3.036	10.344
		3	2.978	10.150	3.574	12.180
		3-1/2	3.970	13.530	4.764	16.236
		4	5.620	19.130	6.744	22.956
Single bevel		1/4	0.063	0.215	0.069	0.237
		3/8	0.117	0.364	0.129	0.400
		1/2	0.188	0.641	0.207	0.705
		5/8	0.301	1.025	0.331	1.128
		3/4	0.375	1.280	0.413	1.408
		1	0.625	2.135	0.687	2.349
Double bevel		5/8	0.176	0.600	0.211	0.720
		3/4	0.234	0.798	0.281	0.958
		7/8	0.301	1.025	0.361	1.230
		1	0.375	1.279	0.450	1.535
		1-1/4	0.547	1.862	0.656	2.234
		1-1/2	0.750	2.560	0.900	3.072
		1-3/4	0.984	3.360	1.181	4.032
		2	1.250	4.260	1.500	5.112
		2-1/2	1.875	6.398	2.250	7.677
		3	2.625	8.950	3.150	10.740

FIGURE 20-2 Area and weight of weld metal deposit.

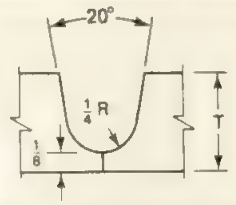
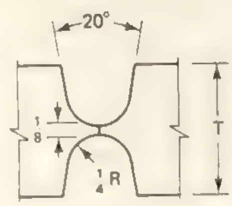
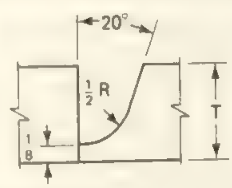
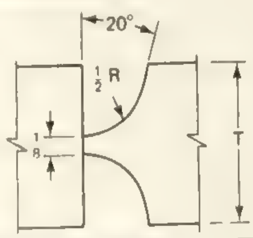
Weld	Design	T in inch	CSA Theor. in.^{2}	Weld Deposit Theoretical lb/ft	CSA w/ref. in.^{2}	Weld Deposit w/ Reinforcement lb/ft
Single U		1/2	0.163	0.555	0.179	0.611
		3/4	0.310	1.058	0.341	1.164
		7/8	0.392	1.338	0.431	1.472
		1	0.479	1.635	0.527	1.799
		1-1/4	0.671	2.288	0.738	2.517
		1-1/2	0.885	3.020	0.974	3.322
		1-3/4	1.120	3.820	1.232	4.202
		2	1.376	4.680	1.514	5.148
		2-1/2	1.961	6.680	2.157	7.348
		3	2.631	8.960	2.894	9.856
Double U		1	0.396	1.350	0.475	1.620
		1-1/4	0.543	1.852	0.652	2.222
		1-1/2	0.701	2.390	0.841	2.868
		1-3/4	0.870	2.968	1.044	3.562
		2	1.151	3.922	1.381	4.706
		2-1/4	1.242	4.235	1.490	5.082
		2-1/2	1.444	4.925	1.732	5.910
		2-3/4	1.658	5.650	2.000	6.780
		3	1.879	6.410	2.255	7.692
		3-1/2	2.389	8.150	2.867	9.780
		4	2.951	10.070	3.541	12.084
		4-1/2	3.459	11.790	4.151	14.148
Single J		1/2	0.180	0.614	0.198	0.675
		3/4	0.261	0.890	0.287	0.979
		1	0.409	1.395	0.450	1.535
		1-1/4	0.580	1.978	0.638	2.176
		1-1/2	0.774	2.640	0.851	2.904
		1-3/4	0.989	3.375	1.088	3.713
		2	1.229	4.190	1.352	4.609
		2-1/4	1.491	5.080	1.640	5.589
		2-1/2	1.774	6.050	1.951	6.655
Double V		1	0.360	1.228	0.432	1.474
		1-1/4	0.437	1.490	0.524	1.788
		1-1/2	0.589	2.010	0.707	2.412
		1-3/4	0.728	2.482	0.874	2.978
		2	0.875	2.983	1.050	3.580
		2-1/4	1.029	3.510	1.235	4.212
		2-1/2	1.191	4.065	1.429	4.878
		2-3/4	1.360	4.640	1.632	5.568
		3	1.535	5.235	1.842	6.282
		3-1/2	1.909	6.510	2.291	7.812
		4	2.313	7.880	2.776	9.456

FIGURE 20-2 (*cont.*)

weight of weld metal required when the size of a fillet weld is increased. Other comparisons can be made such as the difference in the cross-sectional area or weld metal required between a bevel to a V-groove weld or between a single- and a double-groove weld. They can also be used for torch brazing and for oxyfuel gas welding. These data can be the basis for a standard cost system when standard weld design as shown is used. If the weld designs are different from those used in the charts, the data must be recalculated to reflect these changes.

20-3 FILLER METAL AND MATERIALS REQUIRED

Electrodes

Section 20-2 provided information necessary to calculate the "weight of weld metal deposited" in a weld joint or on a weldment. It also provides tables that give the weight of weld metal deposit for standard weld designs made in different thicknesses of material. The total weight of weld metal deposited in the joint or required to produce the weldment can easily be calculated using these tables.

The weight of filler metal purchased to make the weld or the weldment is greater than the weight of the weld metal deposit. This is true for most of the arc welding processes, but not for all. Stated another way, it means that more filler metal must be purchased than is deposited because of stub end losses, coating or slag losses, spatter losses, and so on. This can be shown by Equation (20-2) (see page 616). These losses are sometimes represented as a ratio and called deposition efficiency, filler metal yield, or recovery rate.

Deposition efficiency is the ratio of the weight of deposited weld metal in the weld devided by the net weight of filler metal consumed, exclusive of stubs: As shown by Equation (20-3), filler metal yield is the ratio of the weight of deposited weld metal divided by the gross weight

$$\text{weight of filler metal required (lb)} = \frac{\text{weight of weld metal deposited (lb)}}{1 - \text{total electrode loss}} \quad (20\text{-}2)$$

$$\text{weight of filler metal required (lb)} = \frac{\text{weight of weld metal deposited (lb)}}{\text{filler metal yield (\%)}} \quad (20\text{-}3)$$

$$\text{electrode cost (\$/ft)} = \frac{\text{electrode price (\$/lb)} \times \text{weld metal deposited (lb/ft)}}{\text{filler metal yield (\%)}} \quad (20\text{-}4)$$

of the filler metal used. Thus yield relates to the amount of filler metal purchased. The filler metal yield for the different types of electrodes and filler metals will range from as low as 50 to 100%. Yield is the better term to use since stubs occur only when using covered electrodes.

The covered electrode has the lowest yield, that is, it has the highest losses. These losses are made up of the stub end loss, the coating or slag loss, and the spatter loss. Considering a 2-in. stub, the 14-in. long electrode has a 14% stub loss, the 18-in. electrode has an 11% stub loss, and the 28-in. electrode has a 7% stub loss. Unfortunately, electrodes are not always melted to a 2-in. stub. The coating or slag loss of a covered electrode can range from 10 to 50%. The thinner coatings on an E6010 electrode are at the lower end of the scale approximating 10% while the heavy coating on an E7028 type electrode will approach 50%. This can apply even when iron powder is incorporated in the coating. For accurate results, measure this factor for the electrodes to be used. The spatter loss depends on the welding technique, but normally ranges from 5 to 15% loss. Thus it is easy to see why the coated electrode has such a low yield.

The solid bare electrode or filler rod has the highest yield since the losses are minimized. Normally, in the continuous electrode wire processes the entire spool or coil of electrode wire is consumed in making the weld. Scrap ends of coils are discarded, but this is usually negligible compared to the total weight. The spatter loss relates to welding process and welding technique. In the submerged arc and electroslag welding processes virtually all of the electrode is deposited in the weld. There is no spatter and, therefore, deposition efficiency or yield approaches 100%. In gas metal arc welding there is a loss from spatter and this amounts to approximately 5% of the electrode melted which provides a deposition efficiency or yield of 95%. In the case of the cold wire processes, gas tungsten arc, plasma arc, and carbon arc, the *cold wire* filler metal is completely used and has a 100% yield.

The flux-cored electrode has slightly higher losses because of the fluxing ingredients within the tubular wire which are consumed and lost as slag. The fluxing materials in the core represent from 10 to 20% of the weight of the electrode. Different types and sizes have different core-to-steel weight ratios. For accurate results measure yield of the electrode to be used. There can be up to 5% loss as spatter; therefore, the deposition efficiency or yield for flux-cored electrodes ranges from 75 to 85%. The deposition effiency or yield of filler material and the process have an important bearing on the cost of the deposited weld metal.

The filler metal cost can be calculated several different ways. The most common is based on cost per foot of weld, as shown by Equation (20-4).

The electrode price is the delivered cost to your plant. Electrode price can be reduced by purchasing in large lot sizes. In this formula the yield can be taken from Figure 20-3. These are average figures and should be sufficient for most calculations; however, for more accuracy actual measurements should be made using the filler metals that are to be employed.

A different method can be used for calculating the amount of weld metal required when the continuous wire processes are used. It is particularly advantageous for single-pass welding. Three simple calculations are required but the end result is the electrode cost per foot of weld. The first step is to determine the amount of elec-

FIGURE 20-3 Filler metal yield for various types of electrodes.

Electrode Type and Process	Yield %
Covered Electrode for:	
SMAW 14" manual	55 to 65%
SMAW 18" manual	60 to 70%
SMAW 28" automatic	65 to 75%
Solid Bare electrode for:	
Submerged arc	95 to 100%
Electroslag	95 to 100%
Gas metal arc welding	90 to 95%
Cold wire use	100%
Tubular-flux cored electrode for:	
Flux cored arc welding	80 to 85%
Cold wire use	100%

Note - Does not include shielding except for covered electrodes.

$$\text{Weight of filler metal required (lb/hr)} = \frac{\text{wire feed speed (in./min)} \times 60}{\text{length of wire per weight (in./lb)}} \quad (20\text{-}5)$$

$$\text{Travel speed (ft/hr)} = \frac{\text{travel speed (in./min)} \times 60}{12} = \text{travel speed (in./min)} \times 5 \quad (20\text{-}6)$$

$$\text{Weight of filler metal required (lb/ft)} = \frac{\text{deposition rate (lb/hr)}}{\text{weld travel speed (in./min)} \times 5} \quad (20\text{-}7)$$

trode used expressed as pounds per hour, using Equation (20-5).

The pounds per hour of electrode used disregards the yield or deposition rate factor since we are measuring the actual filler material consumed. The factor 60 is the minutes in an hour, which converts minutes to hours. The weight per length of the electrode wire is a physical property of wire based on the size of the wire and the density of the metal of the wire (Figure 20-4). The wire feed speed in inches per minute is the same as the melt off rate of an electrode wire. It is not a true deposition rate since the spatter losses and slag losses are not considered. The wire feed speed can be determined from charts that relate the welding current to the wire feed speed, according to the size of the electrode wire, the composition of the electrode wire, and the welding process. Charts showing these data are given in Section 11-2 on wire feeders. To use this formula it is essential to know the welding current or to measure the wire feed speed. In some instances wire feed speed is called for in the welding procedure. For very accurate work it is best to make a measurement of wire feed speed. This can be done simply by setting the wire feeder, making a test weld to determine that the weld procedure is satisfactory, and then without welding, actually allow the electrode wire to feed through the gun and measure the amount of wire fed per minute. Since this can be an extremely large amount of wire, it can be simplified by feeding for 5 seconds and multiplying the amount of wire fed by 12 to relate it to inches per minute. Instruments are available for making this measurement.

The second part of this calculation is to determine or measure the weld travel speed and arrive at this rate in feet per hour. Normally, welding procedures provide weld travel speed in inches per minute. If these data are not in the welding procedure, tests should be made to determine travel speed while making the required weld. This is then converted to feet per hour by using Equation (20-6). The 60 represents minutes in an hour and the 12 represents inches in a foot, which is the factor 5 previously mentioned.

The third part of this calculation is to determine the weight of weld metal required per foot of weld, as shown by using Equation (20-7).

The above information would then be multiplied by the electrode price ($/lb) to obtain electrode cost in $/ft.

This system can also be used for flux-cored arc

FIGURE 20-4 Length versus weight (inches per pound) of bare electrode wire of type and size shown.

Wire Diameter		Inches of Metal or Alloy per Pound								
Decimal Inches	Fraction Inches	Aluminum	Alum. 10% Bronze	Silicon Bronze	Copper (deox.)	Copper Nickel	Magnesium	Nickel	Steel, Mild	Steel, Stainless
0.020		32,400	11,600	10,300	9800	9950	50,500	9900	11,100	10,950
0.025		22,300	7,960	7,100	6750	6820	34,700	6820	7,680	7,550
0.030		14,420	5,150	4,600	4360	4430	22,400	4400	4,960	4,880
0.035		10,600	3,780	3,380	3200	3260	16,500	3240	3,650	3,590
0.040		8,120	2,900	2,580	2450	2490	12,600	2480	2,790	2,750
0.045	3/64	6,410	2,290	2,040	1940	1970	9,990	1960	2,210	2,170
0.062	1/16	3,382	1,120	1,070	1020	1040	5,270	1030	1,160	1,140
0.078	5/64	2,120	756	675	640	650	3,300	647	730	718
0.093	3/32	1,510	538	510	455	462	2,350	460	519	510
0.125	1/8	825	295	263	249	253	1,280	252	284	279
0.156	5/32	530	189	169	160	163	825	162	182	179
0.187	3/16	377	134	120	114	116	587	115	130	127
0.250	1/4	206	74	66	62	64	320	63	71	70

$$\text{Flux cost (\$/ft)} = \text{flux price (\$/lb)} \times \text{weld metal deposit (lb/ft)} \times \text{flux ratio} \qquad (20\text{-}8)$$

Electrode Size-Dia. (Inch)	Length by Weight (Inches/Pound)
0.045	2400
1/16	1250
5/64	1000
3/32	650
7/64	470
0.120	380
1/8	345
5/32	225

FIGURE 20-5 Length per pound of steel flux-cored electrode wire.

welding, but in this case the length of electrode wire per pound is a little more difficult to determine since different types of flux-cored wire have different amounts of core material of different densities (see Figure 20-5). The length per pound of steel flux-cored electrode wire can be used for normal calculations. For better accuracy, actual tests should be made to determine the number of inches of the wire that weighs a pound.

Flux

When flux is used the cost of flux must be included in the cost of materials used. The cost of flux in submerged arc welding and in electroslag welding and even in oxyfuel gas welding can be related to the weight of weld metal deposited and may be calculated using Equation (20–8).

In the submerged arc welding process normally one pound of submerged arc flux is used with each pound of electrode wire deposited. This is a flux-to-steel ratio of one. This ratio may change for different welding procedures and for different types of flux.

The flux ratio of 1 can be used for costing; however, for more accuracy, tests should be run with the particular flux used. The flux ratio can rise as high as 1.5.

For electroslag welding the ratio of flux to electrode wire deposited is 5 to 10 lb of flux per 100 lb of electrode consumed. This is a flux-to-steel ratio of 0.05 to 0.10. The exact amount of flux used is based on the surface area of retaining shoes exposed to the flux pool. The rule of thumb is ¼ lb of flux per vertical foot of joint height. The 10% ratio mentioned above is ample to cover the cost of electroslag flux.

In oxyfuel gas welding and torch brazing the amount of flux used can also be related to the amount of filler wire consumed. This ratio is usually on the order of 5 to 10%. Accurate checks can be made for a more precise flux ratio if desired.

Shielding Gas

When shielding gas is used it must be included in material cost. The cost of the gas is related to the time required to make the weld. Shielding gas is normally used at a specified flow rate and measured in cubic feet per hour. The amount of shielding gas used would be the time required to make the weld, times the rate of gas usage. The cost of shielding gas can be figured two ways. Normally, the gas cost is based on the cost per foot of the weld and it is calculated using Equation (20-9).

The gas flow rate is provided in the welding procedure or it can be measured with a flow meter. The price of gas is the delivered price at the welding station.

Shielding gas cost per minute of operation is used when calculating the cost of making an arc spot weld, a small joint, or a small part. This is based on the time required to make the weld and it may be calculated using Equation (20-10).

Miscellaneous Material Costs

To obtain a total cost of a particular weld other items should be included. These include the guide tube used in the consumable guide electroslag welding process, the cost of ferrules and studs in arc stud welding, and so on. In stud welding the price of each stud must be considered, even though studs are not strictly filler metals. They relate to the number of welds made and can be calculated in this manner. Also, since a ceramic ferrule is required for each weld they must also be included in the cost of making each stud weld.

20-4 TIME AND LABOR REQUIRED

The cost of the labor required to make a weld is perhaps the single greatest factor in the total cost of a weld. Section 20-3 provided the weight of metal deposit for different welds of different sizes. With this information, the cost of the filler metals required is determined. The amount of weld deposit or the amount of filler metal required is one basis for determining the amount of time required to make a weld or weldment. Time is normally the basis for pay for welders since many are paid by the per hour rate. The data that follow will be used to determine the cost of welding when welders are paid an hourly rate.

Welders are sometimes paid on the basis of welds made. This may be on a per footage basis for different size welds or on the number of pieces welded per hour. This type of pay is usually involved with incentive systems. In order to establish costs on this basis it may

$$\text{gas cost (\$/ft)} = \frac{\text{price of gas (\$/ft}^3\text{)} \times \text{flow rate (ft}^3\text{/hr)}}{\text{weld travel speed (in./min)} \times 5} \tag{20-9}$$

$$\text{gas cost (\$/weld)} = \frac{\text{price of gas (\$/ft}^3\text{)} \times \text{flow rate (ft}^3\text{/hr)} \times \text{weld time (min)}}{60} \tag{20-10}$$

$$\text{labor cost (\$/ft)} = \frac{\text{welder pay rate (\$/hr)}}{\text{Travel speed (in./min)} \times \text{operator factor (\%)} \times 5} \tag{20-11}$$

be necessary to determine time required for making welds of different types or, conversely, the speed of making certain welds. In some cases, time studies are used to determine the normal welding time for making a particular weld or weldment. In other cases, standard cost data are used and quite often these are based on weight of weld metal deposited. In developing the cost of welds, these data can be used in many different ways according to the pay systems and accounting systems employed. The basis for accurate weld costing is a welding procedure. The welding procedure may not be available at the time of setting cost standards or estimating costs, therefore, welding procedure schedules like those presented throughout this book should be employed.

The basis for calculating the cost of labor on a dollars-per-foot basis is given in Equation (20-11). The operator factor shown here is the same as duty cycle, which is the percentage of arc time against the total paid time.

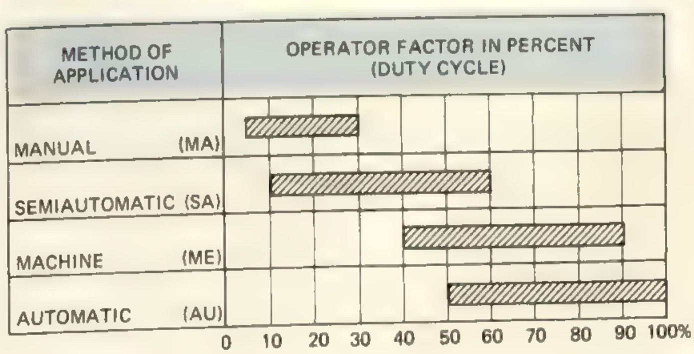
Each of the elements of this formula requires considerable analysis. The welder's hourly pay rate can be entered into the formula; however, in most cases companies prefer to factor the pay rate to cover fringe benefits such as cost of insurance, cost of holidays, cost of vacations, and so on. This is a factor that must be determined and must be in line with the company accounting policies. It should be the same as the method used for determining machining costs and other direct labors costs used in the plant.

The assumption above applies primarily to single-pass welds, since weld travel speed is available in the welding procedure schedules. It should be used when metal is not deposited, specifically GTAW and PAW. Travel speeds relate to the welding job, the weld type, and the welding process employed. This is relatively easy to determine when single-pass welds are made, but it is more difficult with multipass welds and for this reason a different system is used for large multipass welds.

Duty cycle or operator factor also requires analysis since it varies considerably from job to job and from process to process. The shielded metal arc welding process has the lowest operator factor while semiautomatic welding is much higher, often double. The type of work dictates the operator factor. Construction work, in which small welds are made in scattered locations, has a low operator factor. Heavy production work in which large welds are made on heavy weldments can have much higher operator factors. Time study is sometimes used to determine operator factor based on work similar to the job being costed. Automatic time recorders are sometimes used to accurately determine operator factor on repetitive jobs. The results of this calculation provide labor costs in dollars per foot of weld joint. This can be added to the cost per foot of materials, filler metals, and so on.

As an estimate for operator factor, when other data are not available, refer to Figure 20-6. This shows the operator factor related to the method of applying the weld. The arrangement of the work, the use of positioners and fixtures, whether the work is indoors or outdoors, all have an effect on the operator factor. Construction would tend to be the lower end of the range with heavy production toward the high end of the range. The operator factor will vary from plant to plant, and it will also vary from part to part if the amount of weld is much different. The operator factor is higher for the continuous electrode wire processes since the welder does not have to stop every time a covered electrode is consumed. Slag

FIGURE 20-6 Welder operator factor related to method of application.



$$\text{Labor cost (\$/ft)} = \frac{\text{welder pay rate (\$/hr)} \times \text{weight of weld metal deposit (lb/ft)}}{\text{deposition rate (lb/hr)} \times \text{operator factor (\%)}} \qquad (20\text{-}12)$$

chipping, electrode changes, and moving from one joint to another all reduce the operator factor.

When the welding procedure schedule is not available or when travel speed involves more than one pass, Equation (20-12) is used.

The weight of weld metal deposit in pounds per foot is the datum presented in Figure 20-2. As mentioned previously, this can be changed for different metals if the density of the metal is used in the formula. This datum is universal when the proper density factor is used.

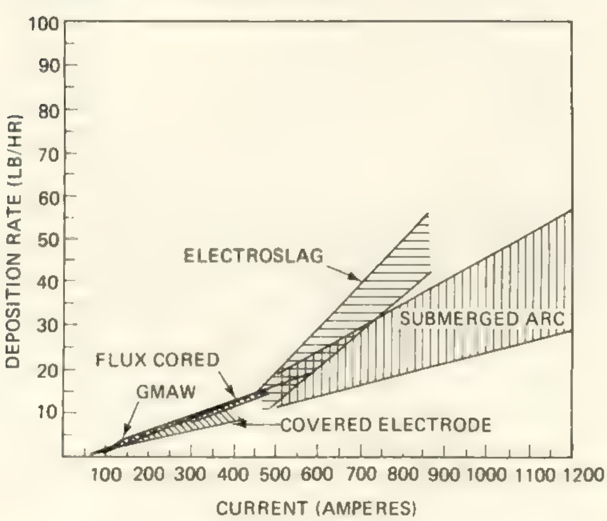
The new factor introduced by this formula is deposition rate in pounds per hour. Deposition rate is the weight of the filler metal deposited in a unit of time. It is expressed as pounds per hour. Charts and graphs presented in the sections for particular processes provide deposition rate information. Figure 20-7 is a composite chart covering most of these processes using steel electrodes. The deposition rate has a tremendous effect on welding costs. The greater the deposition rate, usually the less time required to make a weld. This should be tempered, however, since certain high-deposition-rate processes cannot be applied to smaller jobs. For accurate results it is necessary to calculate deposition rates for specific weld procedures. This can be done by weighing the filler metal used, weighing the weld metal deposited, and measuring the arc time. This will provide the deposition rate and also the filler metal yield or utilization.

Deposition rate can also be calculated. This requires the use of Figures 11-20 to 11-22. These curves show the electrode wire feed speed per minute versus welding current. The melt-off rate and the wire feed speed are the same. The curves can be used for these calculations. The melt-off rates are given in inches per minute based on the type and size of electrode, the welding process and current. Figure 20-4 shows the length of bare electrode wire per pound of different metals. The relationship between melt-off rate and weight of filler metal melted can be determined by using the equation (20-13).

Use the wire feed speed graphs for melt-off rate and use Figure 20-4 for the length and weight of electrode wire.

The deposition rate, which is pounds of metal deposited per hour, is related to the melt-off rate by dividing melt-off rate by the filler metal yield or deposition efficiency. For solid wire systems the yield is high, as shown in Figure 20-3.

FIGURE 20-7 Deposition rates for various processes with steel electrodes.



20-5 POWER AND OVERHEAD COSTS

Overhead cost consists of many, many things, both in the factory and in the office. It consists of the salaries of plant executives, supervisors, inspectors, maintenance personnel, janitors, and others for whom their time cannot be directly charged to the individual job or weldment. These costs are apportioned pro rata among all work going through the plant. Another important overhead cost is rent or depreciation of the plant and the general maintenance of the building, grounds, and so on. Depreciation of plant equipment includes welding machines, materials-handling equipment, overhead cranes, and all other equipment that is not charged directly to individual or specific weldments. In addition, all the taxes on the plant, the real estate, equipment, payroll, and any other taxes applying to the operation of the plant are considered as overhead. Another item of overhead is the small tools such as chipping hammers, electrode holders, safety equipment, and so on, that are not charged to specific jobs. In addition, in most plants the cost of heat, lights, maintenance and repair of the building and equipment are also charged to overhead accounts.

Almost all plants or factories have similar systems for handling overhead expenses but they vary in detail and for this reason cannot be described here. In all cases, however, the overhead charges must be distributed to the welding jobs in one manner or another. In some cases this is based on a per ton of steel fabricated or on the weight of steel consumed. Usually, however, the overhead costs are prorated in accordance to the direct labor charges against the different welding jobs. When this

$$\text{deposition rate (lb/hr)} = \frac{\text{melt-off rate (in./min)} \times 60}{\text{length of electrode wire per weight (in./lb)} \times \text{FM yield (\%)}} \qquad (20\text{-}13)$$

$$\text{overhead cost (\$/ft)} = \frac{\text{overhead rate (\$/hr)}}{\text{travel speed (in./min)} \times \text{operator factor (\%)} \times 5} \qquad (20\text{-}14)$$

$$\text{overhead cost (\$/ft)} = \frac{\text{overhead rate (\$/hr)} \times \text{weight of weld metal deposit (lb/ft)}}{\text{deposition rate (lb/hr)} \times \text{operator factor (\%)}} \qquad (20\text{-}15)$$

$$\text{power cost (\$/ft)} = \frac{\text{local power rate (\$/kWh)} \times \text{volts} \times \text{amperes} \times \text{weld metal deposit (lb/ft)}}{1000 \times \text{deposition rate (lb/hr)} \times \text{operator factor (\%)} \times \text{power source efficiency (\%)}} \qquad (20\text{-}16)$$

system is used accurate labor costs for weldments are essential.

Overhead rates are sometimes separate and not included in the welder pay rate. When this is the case the same formulas as described before [i.e., Equations (20-10) and (20-11)] are used, but the overhead rate is substituted for the welder's pay rate. Both are in dollars per hour.

For single-pass welding, use Equation (20-14). Duty cycle and operator factor are the same.

For multipass welding Equation (20-15) should be used.

The cost of electrical power is sometimes considered part of the overhead expense. On the other hand, when it is necessary to compare competing manufacturing processes or competing welding processes it is wise to include the cost of electric power in the calculations. In some plants electric power is considered a direct cost and is charged against the particular job. This is more often the case for field welding than for large production weldment shops. In this case, Equation (20-16) is used.

The local power rate is based on the rate charged to the factory by the local utility company. If time penalties, power factor penalties, and so on, are involved, they should be included. The volts and amperes are the values used when making the weld. The weight of the weld metal is the weight of the weld metal deposited. The deposition rate is that used for a particular weld, as is the operator factor. The final factor is the efficiency of the power source, and this can be found from the machine performance curve. Performance curves were presented in Chapter 10.

Special fixtures for tack welding and holding may be considered an indirect labor cost and are classed as overhead. These items are considered as capital expenditures and are depreciated over a period of five years or so. These costs are also added to the welding department or plant overhead. When this information is calculated, it is added to overhead costs, the cost of labor, and the cost of filler metal to arrive at the total weld cost.

20-6 WELD COST FORMULAS AND EXAMPLES

Welding costs are obtained by adding the major cost elements:

- *Materials cost:* filler metals, flux, gas, etc.
- *Labor cost:* direct labor
- *Overhead cost:* normally prorated to direct labor

One method of calculating cost is using the basis of cost per weld. This is used for arc spot welds (sometimes cost is based on per 100 arc spot welds), for plug welds, and for small welds used to make a small part.

The more common method of calculating welding cost is on the basis of cost per foot of weld. Each of the cost elements mentioned above can be determined on this basis. There are several ways of determining the cost of the principal elements. One method is best for single-pass welding with continuous wire processes and the other is best for multipass welding.

Material Cost

For all welding processes that utilize deposited metal, the weight of deposited metal is the basis for material costs. The weight of each type of weld in the weldment is calculated and the results are added together to determine the total weight. Use Equation (20-3) (see page 616). The weight of weld metal deposit for each weld type is obtained from Figure 20-2. Filler metal yield is based on the type of filler metal and the data of Figure 20-3. These results can be factored by the electrode price to obtain the cost of filler metal required.

To determine the electrode cost per foot use Equation (20-4) (see page 616). Obtain the weld metal deposit from Figure 20-2. The electrode price is the delivered cost to the plant, and the filler metal yield is from Figure 20-3.

Another method of determining the weight of filler metal required, when using a continuous electrode wire process, is to use Equation (20-5) (see page 617). The wire feed speed is taken from the welding procedure, or can be obtained from the process schedule charts based on welding current, or it can be measured. The length of wire per weight is taken from Figure 20-4.

A third method of determining filler metal required is to use Equation (20-7) (see page 617). The weld travel speed can be obtained from the welding procedure, or from process schedule charts, or by measurement. The deposition rate is arrived at from process deposition rate charts based on the current or by Equation (20-13) (see page 621).

The wire feed rate is obtained from the welding procedure, from charts based on welding current, or by measurement. The other two factors were mentioned above.

The cost of welding flux used for SAW is determined by using Equation (20-8) (see page 618). The flux price is the delivered cost to the plant. The weld metal deposit is computed using Equation (20-1) (see page 611), or from Figure 20-2. The flux ratio is 1, 1.1, or 1.2. For accuracy make a test and measure the weld deposit and flux consumed and establish the ratio.

The cost of shielding gas per foot for GMAW, FCAW or GTAW is determined by using Equation (20-9) (see page 619). The price of gas is the cost of the shielding gas delivered to the plant. The flow rate is the usage and is from the welding procedure, from process schedule charts, or by measurement. The welding travel speed is obtained the same way.

The cost of shielding gas per weld is used when costing arc spot welds, plug welds, or small weldments and is determined by using Equation (20-10) (see page 619). The price of gas and the flow rate are obtained as mentioned above. The weld time is established by the welding procedure, or from process schedule charts or by measurement.

Labor and Overhead Cost

The labor and overhead cost for single-pass welding is determined by using Equation (20-11) (see page 619). The welder pay rate is normally factored to cover fringe benefits. The travel speed is taken from the welding procedure, process schedule charts, or is measured. The operator factor, or duty cycle, is obtained from Figure 20-5; however, for better accuracy it should be measured, or related to similar jobs.

The labor and overhead cost for multipass welding is determined by using Equation (20-12) (see page 620). The data for each factor involved in this formula have been explained above.

The overhead cost must be calculated separately if all of the overhead is not included in the welder pay rate. The equations to use are similar to Equations (20-14) and (20-15) (see page 621). The only difference is that the overhead rate is substituted for the welder pay rate and it should be obtained from the accounting calculations, which is beyond the scope of this book. For simplicity the overhead rate can be assumed to be equal to the welder pay rate. In some plants it is two times the pay rate or even higher.

Sample Cost Calculations

The following examples will show how the different equations are used. The following rates will be used in these examples.

Welder pay rate	= \$15.00 per hour
Overhead rate	= \$30.00 per hour
Power cost	= \$0.06 per kwh
Argon gas cost	= \$0.21 per cubic feet
CO_2 gas cost	= \$0.10 per cubic feet
Covered electrode price	= \$0.48 per pound
Steel electrode wire price	= \$0.55 per pound
Flux-cored electrode price	= \$0.65 per pound

All other data are taken from information referenced elsewhere in this book.

EXAMPLE 1 In this example we wish to establish the cost of a weldment that contains 120 ft of ¼-in. fillet, 300 ft of 3/16-in. fillet, 40 ft of ½-in. V grove, and 60 ft of ⅜-in V-groove weld. To determine the amount of weld metal deposited, consult Figure 20-2. Obtain the weight of weld metal of each type of weld, multiply it by the length of that type of weld, and add the total:

120 ft of ¼-in. fillet	= 12.7 lb
300 ft of 3/16-in. fillet	= 18.3 lb
40 ft of ½-in. V groove	= 28.1 lb
60 ft of ⅜-in. V groove	= 23.0 lb
Total of weld metal deposited	= 82.1 lb

What is the cost of the filler metal required when covered electrodes are used? Use Equation (20-4) (modified) and a filler metal yield of 60% from Figure 20-3:

$$\text{electrode cost (\$)} = \frac{0.48 \times 82.1}{0.60} = \$65.68$$

What is the cost of filler metal required if solid-steel electrodes are used? Use Equation (20-4) (modified) and a filler metal yield of 92.5% from Figure 20-3:

$$\text{electrode cost (\$)} = \frac{0.48 \times 82.1}{0.925} = \$42.60$$

Note that the total cost is less when using a higher-priced electrode.

EXAMPLE 2 What is the cost of a foot of ¼-in. fillet weld made manually with SMAW using E6024 electrode 3/16-in. size? The operator factor is 30% and is from Figure 20-6. The filler metal yield is 55% and is from Figure 20-3. The weight of weld metal deposited is 0.117 lb/ft and is from Figure 20-2. Use Equation (20-4):

$$\text{electrode cost (\$/ft)} = \frac{0.48 \times 0.117}{0.55} = 0.102 \text{ \$/ft}$$

The labor cost is calculated using Equation (20-11). The travel speed of 15 in./min is from the process schedule chart:

$$\text{labor cost (\$/ft)} = \frac{15.00}{15 \times 0.30 \times 5} = \$0.666 \text{ \$/ft}$$

The overhead cost is double the labor cost. The total cost is the total of: \$0.102 + 0.666 + 1.332 = 2.10 \$/ft of weld.

EXAMPLE 3 What is the cost of a foot of ¼-in. fillet weld made semiautomatically using GMAW with CO_2 gas shielding using an E7OS-1 electrode of 0.035 in. size? The operator factor is 50% and is from Figure 20-6. The filler metal yield is 95% and is from Figure 20-3. Use Equation (20-4):

$$\text{electrode cost (\$/ft)} = \frac{0.55 \times 0.117}{0.95} = 0.067 \text{ \$/ft}$$

The gas cost is calculated using Equation (20-9). The shielding gas flow rate is 25 cubic feet per minute and the travel speed is 15 in./min obtained from the process schedule chart:

$$\text{gas cost (\$/ft)} = \frac{0.06 \times 25}{15 \times 5} = 0.024 \text{ \$/ft}$$

The labor cost is determined using Equation (20-11) (all of the factors involved were mentioned above):

$$\text{labor cost (\$/ft)} = \frac{15.00}{15 \times 0.5 \times 5} = 0.399 \text{ \$/ft}$$

The overhead cost is determined using Equation (20-14) (all of the factors involved were mentioned above):

$$\text{overhead cost (\$/ft)} = \frac{30}{15 \times 0.5 \times 5} = 0.80 \text{ \$/ft}$$

The total cost is the total of: 0.067 + 0.024 + 0.399 + 0.80 = 1.29 \$/ft of weld. Note that the gas metal arc is less expensive than shielded metal arc welding for the same weld size.

EXAMPLE 4 How many pounds of E7OS-1 electrode wire 0.035 in. in diameter shuld be purchased to make a tank requiring 25,500 ft of ¼-in. square groove butt weld? The weld depósit, with reinforcement, is 0.065 lb/ft from Figure 20-2, times 25,500 ft. which is 1657.5 lb. To determine the pounds of filler metal needed, use Equation (20-3) (the filler metal yield of 90% is from Figure 20-3):

$$\text{Weight of filler metal required (lb)} = \frac{1657.5}{0.90} = 1842 \text{ lb}$$

These computations are quickly made using an electronic calculator.

QUESTIONS

20-1. Why is the cross-sectional area of a weld joint important to cost?

20-2. What is the formula for the cross-sectional area of a regular fillet weld?

20-3. If the cross-sectional area is known, how do you determine the weight of a foot of weld?

20-4. What is filler metal yield? Why is the yield lower for covered electrodes?

20-5. Which has the better yield, a 14-in. electrode or an 18-in. electrode? Why?

20-6. Why is deposition rate so important for welding costs?

20-7. What different materials are included in gas metal arc welding? In submerged arc welding? In shielded metal arc welding?

20-8. What is the operator factor when calculating welding cost?

20-9. Why is operator factor so important?

20-10. What major cost elements must be totaled to obtain total welding cost?

20-11. How does poor fitup affect welding costs?

The manufacturing system provides management support through policy and delegated authority. The system includes documentation to establish designs, manufacturing techniques, and quality control methods. From a welding point of view it includes welding procedure qualifications, welder performance qualifications, and an overall total welding quality control program.

The purpose of a welding procedure qualification[2] is to show that the proposed weldment will have the required properties for its intended application, that is, to determine the properties of a sound weld. The document that does this is the Procedure Qualification Record (PQR). This provides the actual welding variables used to produce an acceptable test weld and the results of tests conducted.

The purpose of the welder performance qualification test is to determine the ability of the welder or welding operator to deposit sound weld metal following a welding procedure specification. The document that does this is the Performance Qualification Test Record. This qualifies the welder or welding operator for specific processes, for different welds, positions, and thicknesses.

Neither the welding procedure qualification nor the welder performance qualification establish the capability of the organization or the welding equipment to make an acceptable welded product. Therefore, a quality control program must be developed and implemented. The quality control or assurance program establishes: the authority and responsibility; the design basis, procurement and material control, manufacturing technology, the selection and application of welding processes and equipment; the necessary fixtures and tooling; pre- and postheating requirements; the calibration of the equipment; the training and indoctrinating of welders and supervision; and the commitment of all levels of management to high-quality products.

The remaining portion of this section concerns the quality control plan and offers a suggested quality control program. It can be adopted by companies desiring to improve weld quality and is very similar to programs established by some of the nuclear codes.

Quality welding on any product must be judged with respect to a specific quality standard, which must be based on the intended service of the product. It must be balanced between the service requirements and the consequence of failure versus economic factors. For many products, in many industries, weld quality requirements are controlled by applicable codes and specifications. However, when no codes or specifications apply, the producer must maintain high product quality in order to survive. The success of maintaining the balance between high quality and high cost is decided in the field and in the marketplace, where quality and price determine the producer's continuing success.

The weldments included in space vehicles and nuclear vessels are exposed to environments unheard of in the recent past. The weld perfection demanded and obtained by this class of work has been possible thanks to excellent procedures, extensive training, and stringent quality assurance methods. This quality level is attained because of extensive preparation and time-consuming procedures, testing, and qualification, which contribute to high cost. However, perfect welds are not required on every type of weldment. The welding industry must guard against establishing super-quality requirements when they are not required.

The responsibility for producing high-quality products rests on many people. It is the responsibility of management to create the proper cooperative spirit among designers, managers, welders and other production workers, supervisors, and quality control and inspection personnel to make sure that the quality requirement is reasonable and in agreement with the service expected. The responsibility for producing high-quality welds rests on the welder. Each welder must accept this responsibility. The welding supervisor has the responsibility for the welders and for their performance. The welding inspectors must verify that quality standards are met. The welding standards or specifications and procedures are the basis for weld quality, and these factors coupled with the weldment design are the responsibility of designers, welding engineers, material managers, and quality assurance personnel. It is a total responsibility with all involved. This interrelationship is very complex.

The designers, the specification writers, material specifiers, and others must keep close contact with field requirements and problems. They must be sensitive to needs for change and they must be able to relax or tighten standards when needed. Welding supervisors and production managers must be continually alert for evidence of substandard workmanship.

The need to differentiate between the adequate and the perfect weld had led to research concerning the acceptability of weld imperfection and how these imperfections affect service life. This has led to investigations of the degree of imperfection and the fitness for purpose of the weldment. Through the years these data have been translated into codes and specifications for different types of equipment. The knowledge gained from field experience and experience producing weldments is reflected in the revisions of the codes.

A major problem encountered in weldment production is the suspicion of the designer that the weldment will not be manufactured as designed. The suspicion occurs when designers consider workmanship factors that are seemingly beyond their control. They feel that the welder can produce joints equal to the design requirements under ideal conditions and that the welder did produce a good-quality weld when the performance qualification test was passed; however, they want assurance

that every weld in the weldment will be of this quality. For positive assurance it is necessary to implement a quality control program. Such programs save money in the long run, as they eliminate the problem of premature field failures, catastrophic disasters, or the cost of overwelding to overcome suspected shop malpractice.

Quality Control Program

For certain classes of work quality control requirements are well established. These requirements make it necessary to write a quality control program. Strict requirements which are found in the nuclear codes require a quality assurance program that is based on the technical and manufacturing aspects of the product. The program must ensure adequate quality from the design, acquisition, and manufacture, to final shipment. The program must define authority and responsibility for each portion of the work. The quality assurance plan must include the following:

1. *Organization.* The organization for quality must be clearly prescribed. It should define and show charts for responsibility and authority and the organizational freedom to identify and evaluate quality problems. Quality control personnel should not report to production personnel.
2. *Quality assurance program.* The producer must conduct a review of the requirements of the quality required of the product. The various factors, such as specialized controls, processes, testing equipment, and skills, for assuring product quality must be identified. This program must be documented by written policies, procedures, and instructions.
3. *Design control.* The design control must provide for verifying or checking the adequacy of the design, via performance testing and independent review. It should include qualification and testing of prototypes and must conform to specifications. Measures must be established to ensure that the design specifications and code requirements are correctly translated into drawings, procedures, and instructions.
4. *Procurement document control.* The program requires that specifications be written for each item purchased and that the specification ensure the quality required by the end product. These specifications also require quality assurance programs from vendors.
5. *Instructions, procedures, and drawings.* The quality program must ensure that all work affecting quality must be prescribed in clear and complete documented instructions of a type appropriate to the work. Compliance with instructions must be monitored.
6. *Document control.* The quality program must include a procedure for maintaining the completeness and correctness of drawings and instructions, and the like, showing dates, control, effective point, and so on. These drawings, procedures, and instructions must be maintained and continuity explained by change notices.
7. *Control of purchased material, equipment, and services.* The program must include a control system for purchasing from qualified vendors. This means that vendors must have similar quality programs for producing their items. A qualified products list is required and only those vendors having adequate quality programs and providing quality parts will be included. The program requires receiving inspection systems so that purchased parts can be checked against the specifications. Raw materials, purchased parts, and the like will be inspected by means of instruments, laboratory procedures, and so on, to ensure that the products meet the specifications.
8. *Identification and control of materials.* The program must provide for identification of all parts, materials, components, and so on, from receipt throughout all processing to the final item. Records shall provide traceability of all materials, components, and so on. A checklist shall be established for all characteristics to be reported and to record that the test reports have been received, reviewed, and found acceptable.
9. *Control of special processes.* The quality program must ensure that all manufacturing operations including welding are accomplished under controlled conditions. These controlled conditions involve the use of documented work instructions, drawings, special equipment, and so on. It further requires that such instructions be provided, with space for reporting results of inspection by the manufacturer and the inspector, including the date and initials.
10. *Inspection.* The quality assurance program should ensure a system of inspection and testing for all products. Such testing should simulate the product service and records must be maintained of the adequacy of the product to meet these specifications.
11. *Test control.* The program must assure that all tests are performed according to written instructions. Instructions must provide requirements and acceptance limits. Test results must be documented and evaluated to assure that test requirements are met.
12. *Control of measuring and testing equipment.* The program should provide for methods of maintaining the accuracy of gauges, testing devices, meters, and other precision devices, showing that they are calibrated against certified measurement standards on a periodic basis.

They are also very similar to the requirements of the Maritime Administration for commercial ships.[11] Qualification of welders is usually transferable among these three organizations. The American Bureau of Shipping has similar requirements for welding on ships that they survey.[12] Lloyd's and other classification societies also publish specifications that cover welding. Certification of filler metal is required. The American Welding Society publishes two guides related to ship welding: "Guide for Steel Hull Welding"[13] and "Guide for Aluminum Hull Welding."[14]

Storage Tanks and Vessels

There are two major codes for the welding of storage tanks. One is for the welding of elevated storage tanks and is published by AWS and the American Water Works Association, "Standard for Welded Steel Elevated Tanks, Standpipes, and Reservoirs for Water Storage."[15] The other one is for oil or petroleum products storage tanks published by American Petroleum Institute, "Standard for Welded Steel Tanks for Oil Storage."[16] Both of these codes refer to Section IX of the ASME boiler code as far as welding qualification is concerned.

Railroad Rolling Stock

Specifications for manufacturing of rolling stock for North American railroads is under the jurisdiction of the Department of Transportation in the United States. However, as far as welding qualification and welding design requirements are concerned, the controlling specifications are issued by the Association of American Railroads. Various specifications are involved including "Specifications for Tank Cars"[17] and "Specifications for Design, Fabrication, and Construction of Freight Cars."[18] These specifications provide information concerning the design of welds and the qualification of welders' manufacturing these products. They are in substantial agreement with requirements of the AWS "Railroad Welding Specification."[19]

The Department of Transportation also has codes covering the manufacture of tanks for transporting gas under high pressure[20] and for tanks carrying liquid petroleum and similar products.[21]

Aerospace and Aircraft

Weldments intended for use in aircraft and spacecraft are welded to the requirements of U.S. government specifications. There are other groups that write specifications for materials that might be utilized, including the Society of Automotive Engineers[22] and the Aerospace Industries Association of America.[23] Welding codes or requirements are covered by specifications of the National Aeronautics and Space Administration (NASA) and of the Department of Defense Military (Mil) Standards and Specifications. The one pertaining primarily to welding on aircraft is "Qualification of Aircraft, Missile and Aerospace Fusion Welders."[24] This standard covers many welding processes, metals, and levels of proficiency for testing welders and must be adhered to when welding on aircraft. Qualification under this standard is done under the supervision of government inspectors.

Construction Equipment

Construction equipment is made to company standards which have been found acceptable based on the product acceptance in the field. Most manufacturers of construction equipment have their own specifications. The American Welding Society has issued specifications that establish common acceptance standards for weld performance known as "Welding on Earth moving and Construction Equipment."[25] Qualification of welders is not a major issue in this standard.

Industrial Machinery

Most industrial machinery utilizing weldments is not covered by code or specification. The American Welding Society has issued specifications which establish common accepted standards for weld performance and process application. Some of these are:

- "Welding Industrial and Mill Cranes"[26]
- "Metal Cutting Machine Tool Weldments"[27]
- "Specifications for Welding of Presses and Press Components"[28]
- "Specification for Rotating Elements of Equipment"[29]
- "Classification and Application of Welded Joints for Machinery and Equipment"[30]

The welder qualification requirements are similar to the requirements of AWS structural code.

Automotive

The American Welding Society has issued a number of documents relating to welding of automobiles and trucks. They are:

- "Recommended Practices for Automotive Welding Design"[31]
- "Recommended Practices for Automotive Portable Gun-Resistance Spot Welding"[32]
- "Standard for Automotive Resistance Spot Welding Electrodes"[33]
- "Specifications for Automotive Welding Quality—Resistance Spot Welding"[34]

- "Specifications for Automotive Frame Weld Quality—Arc Welding"[35]

General

The American Welding Society document "Standard for Welding Procedure and Performance Qualifications"[36] may become the reference document for qualifying procedures and performance for all AWS product codes, standards, or specifications. It may be used in contract documents. In using any code or specification it is important to use the latest edition or the specific edition involved.

21-3 WELDING PROCEDURES AND QUALIFYING THEM

The subject of welding procedures has become extremely complicated because of the different terminology and definitions of the various welding codes. In view of this it is necessary to consult the latest or specified edition of the code involved and follow it in detail.

In general, "a welding procedure is the detailed methods and practices involved in the production of a weldment."[37] This is a very broad definition and covers two types of procedures. The first is the legal requirements of a code or specification. The second is broader and can be step-by-step directions for making a specific weldment. Procedures of this type are written to maintain consistency, to help reduce weld distortion, or to show how a weldment should be built.

The written welding procedure, required by codes, comprises the step-by-step directions for making a specific weld and proof that the weld is acceptable. This type of procedure consists of three parts:

1. A written explanation describing the conditions involved
2. A drawing of the weld joint and a table giving the welding parameters
3. An information data sheet showing the results of testing the welds and stating that they met the requirements

All welding codes and specifications are similar with respect to procedures. In every case it is necessary to write up the welding procedure and then to prove or qualify it. The problem is with the terminology, which is different in many codes.

Most codes also require proof that welders and welding operators have the necessary skill and ability to follow the welding procedure successfully. This requires that welders and welding operators make specific welds, which are then tested to prove that the welder can produce the weld quality required. This routine is different in different codes and was briefly covered in the section "Qualifying and Certifying Welders."

Many consensus standards, codes, and specifications are adopted by political subdivisions such as cities, states, and provinces. When this is done, the provisions of the referenced code or specifications become a legal document. They may also become legal documents when specified by a contract or purchase order.

Companies develop and qualify welding procedures necessary to manufacture their products that are built under code. Contractors have qualified welding procedures enabling them to install code products. Utilities, with power plants, also have qualified procedures and personnel. In addition, certain special associations have qualified procedures and qualified personnel. This is done in metropolitan areas or where similar work is performed. For example, piping contractors in a large city may form an association to qualify welding procedures and welders. The welders are hired from a labor pool and may work for different contractors on each new job. With this arrangement they are covered by the association's qualified procedures and need not retest for each job. Even with an association the contractor is responsible for the procedures and the welders and for enforcing quality control practices.

The three most popular welding codes cover boilers and pressure vessels, bridges and buildings, and the welding on cross-country transmission pipelines. Each of these codes will be explained by showing examples of the documents required.

Boilers and Pressure Vessels

Section IX of the ASME Boiler and Pressure Vessel Code covers welding and brazing qualifications. It is entitled "Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators."[3]

This code makes the following statement concerning responsibility: "Each manufacturer or contractor is responsible for the welding done by his organization and shall conduct the tests required to qualify the welding procedures he uses in the construction of the weldments built under this code, and the performance of welders and welding operators who apply these procedures." It further states: "Each manufacturer, or contractor, shall maintain a record of the results obtained in welding procedures and welder and welding operator performance qualifications. These records shall be certified by the manufacturer or contractor and shall be accessible to the authorized inspector."

The ASME code calls the welding procedure a *welding procedure specification* (WPS). This document provides in detail the required conditions for specific applications to assure repeatability by properly trained

welders and welding operators. A WPS is a written welding procedure prepared to provide direction for making production welds to code requirements. The ASME provides a sample form, which may be used or modified provided that it covers all information. The WPS provides directions to the welder or welding operator to assure compliance with the code requirements. The completed WPS describes all of the essential, nonessential, and supplementary essential (when required) variables for each welding process. The WPS should reference the supporting procedure qualification record (PQR). A PQR is a record of the welding data used to weld the test coupons. It shows all conditions that were used when welding the test coupons and the actual results of the tested specimens. The completed PQR should record all essential and supplementary essential (when required) variables for each welding process used to weld the test coupon. Nonessential or other variables used during the welding of test coupons need not be recorded. The PQR should be certified accurate by the manufacturer or contractor. This certification is the manufacturer's or contractor's verification that the information is a true record of the variables that were used during the welding of the test coupon and that the test results are in compliance with Section IX of the code. The manufacturer or contractor cannot subcontract this certification function.

There are three types of variables for welding procedure specifications WPS. "Essential variables" are those in which change is considered to affect mechanical properties of the weld joint or weldment. "Supplementary essential variables" are required for metals for which notch toughness tests are required. "Nonessential variables" are those in which a change may be made in the WPS without requalification. The variables for each welding process is listed in detail in Section IX. For this reason it is necessary that you refer to the code when writing, testing, or certifying the welding procedures.

Welding Procedure Specification To help explain the welding procedure specification (WPS), an example is shown in Figures 21-2 to 21-4, which are similar to ASME QW-482. In this example, the ABC Pressure Vessel Company is using the gas metal arc welding process, semiautomatically applied for welding P-1 grade steel pipe in the horizontal fixed and vertical positions. Each entry will be explained briefly.

Joints. The joint design is a single V groove with a 60 to 70° included angle. It is recommended that a sketch be drawn on the form in the area under details. If more space is needed, use a third sheet, such as sheet 3 of 3 (Figure 21-4) in the example. The welding parameters are placed in the table provided. Backing is not used, and backing material need not be described. However, if backing is used, it must be described.

Base Metals. To reduce the number of WPSs required, P numbers are assigned to base metals depending on characteristics such as composition, weldability, and mechanical properties. Groups within P numbers are assigned for ferrous metals for the purpose of procedure qualifications where notch toughness requirements are specified. The same P numbers group the different base metals having comparable characteristics. The P numbers and groupings of most of the different steels are given in the Section IX. Base metal classifications and groupings in AWS B2.1 are slightly different. If a P number is not available for the material involved, its ASTM specification number may be used. If an ASTM specification number is not available, the chemical analysis and mechanical properties can be used. Under base metals the thickness range must be shown, and if it is in pipe, the pipe diameter range must be shown.

Filler Metals. Electrodes and welding rods are grouped according to their usability characteristics, which determines the ability of the welders to make satisfactory welds with a given filler metal. This grouping is made to reduce the number of WPSs needed. The groups are given F numbers, which relate to the composition and usability. This is filled in on the form. This block also requires ASME specification number and the AWS classification number of the filler metal used. The ASME specification numbers are the same as the AWS specification number with the addition of the letters SF. These data are given in ASME Section IX and in the AWS B2.1 document. The AWS classification number for the filler metal specification is also given on the label on the filler metal box. The A number is the classification of weld metal analysis. For example, A-1 has a mild steel weld metal deposit. This classification system is given in both specifications. The size of the filler metal, which is its diameter, must be shown as well as deposited weld metal thickness range for groove or fillet welds. In the case of submerged arc welding, electrode flux class must be shown and the flux trade name must be shown. For gas tungsten arc, the consumable insert analysis should be shown. Other information relating to filler metals not mentioned above should be given, when available.

Position. The welding position of the groove or fillet weld must be described according to AWS terminology. If vertical welding is involved, it should be mentioned whether progression is upward (uphill) or downward (downhill).

Preheat. A minimum temperature shall be given as well as the maximum interpass temperature. Preheat maintenance temperature should be given. Where applicable, special heating should be recorded.

Postweld Heat Treatment. If a postweld heat treatment is used, it must be described. This includes the temperature range and the time at temperature. If there is no postweld heat treatment, write in "none."

Gas. The shielding gas should be identified, and

if it is a mixture, should be described. The shielding gas flow rate should be recorded. If backing gas or trailing shield gas is used, the gas composition should be given and flow rate recorded.

Electrical Characteristics. The welding current should be shown as alternating (ac) or direct current (dc). If direct current is used, the polarity of the electrode should be reported. The amperes and voltage range should be recorded for each electrode size, position, and thickness. This is also presented in a tabular form, as

FIGURE 21-2 ASME welding procedure specifications (WPS), sheet 1.

WELDING PROCEDURE SPECIFICATION (WPS)
(See QW-201.1, Section IX, ASME Boiler and Pressure Vessel Code)

Company Name *ABC Pressure Vessel Company* By: *Frank Jones Weld Engr.*
Welding Procedure Specification No. *1* Date *Aug. 11, 1985* Supporting PQR No.(s) *101*
Revision *~* Date *~*
Welding Process(es) *Gas Metal Arc Welding - Short Circuiting* Type(s) *Semi-Automatic*
(Automatic, Manual, Machine, or Semi-Auto.)

JOINTS (QW-402)

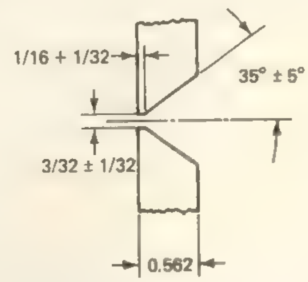
Joint Design *Single Vee*
Backing (Yes) ______ (No) *X*
Backing Material (Type) *~*
(Refer to both backing and retainers.)

☐ Metal ☐ Nonfusing Metal
☐ Nonmetallic ☐ Other

Sketches, Production Drawings, Weld Symbols or Written Description should show the general arrangement of the parts to be welded. Where applicable, the root spacing and the details of weld groove may be specified

(At the option of the Mfgr., sketches may be attached to illustrate joint design, weld layers and bead sequence, e.g. for notch toughness procedures, for multiple process procedures, etc.)

Details



*BASE METALS (QW-403)

P-No. *1* Group No. *1* to P-No. *1* Group No. *1*
OR
Specification type and grade *~*
to Specification type and grade *~*
OR
Chem. Analysis and Mech. Prop. *~*
to Chem. Analysis and Mech. Prop. *~*
Thickness Range:
Base Metal: Groove *up to 1-inch* Fillet *~*
Pipe Dia. Range: Groove *unlimited* Fillet *~*
Other ______

*FILLER METALS (QW-404)

Spec. No. (SFA) *5.18*
AWS No. (Class) *ER 70S-3*
F-No. *6*
A-No. *1*
Size of Filler Metals *0.35-in*
Deposited Weld Metal *~*
Thickness Range: *~*
Groove *1/8-inch*
Fillet *~*
Electrode-Flux (Class) *None*
Flux Trade Name *~*
Consumable Insert *None*
Other *~*

*Each base metal-filler metal combination should be recorded individually.

PQR No. 101

Tensile Test (QW-150)

Specimen No.	Width	Thickness	Area	Ultimate Total Load lb	Ultimate Unit Stress psi	Type of Failure & Location
2G1	0.752	0.377	0.283	26,000	95,500	ductile - BM
2G2	0.754	0.377	0.282	25,400	89,500	ductile - BM
2GU2	0.753	0.378	0.284	21,800	77,000	ductile - BM
2GU4	0.754	0.378	0.284	25,000	88,000	ductile - BM

Guided-Bend Tests (QW-160)

Type and Figure No.	Result
Side bend Q7.1	No defect
Side bend Q7.1	No defect
Side bend Q7.1	No defect
Side bend Q7.1	No defect

Toughness Tests (QW-170)

Specimen No.	Notch Location	Notch Type	Test Temp.	Impact Values	Lateral Exp.		Drop Weight	
					% Shear	Mils	Break	No Break
None								

Fillet-Weld Test (QW-180)

Result — Satisfactory: Yes X No ______ Penetration into Parent Metal: Yes X No ______
Macro—Results Normal

Other Tests

Type of Test None
Deposit Analysis None
Other None

....

Welder's Name Peter J. Arc Clock No. 3506 Stamp No. 506
Tests conducted by: Hobart Procedure Laboratory Laboratory Test No. T-376

We certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of Section IX of the ASME Code.

Manufacturer ABC Pressure Vessel Co

Date Aug. 11, 1985 By John Dough

(Detail of record of tests are illustrative only and may be modified to conform to the type and number of tests required by the Code.)

FIGURE 21-6 ASME procedure qualification record (PQR), sheet 2.

MANUFACTURER'S RECORD OF WELDER OR WELDING OPERATOR QUALIFICATION TESTS (WPQ)
(See QW-301, Section IX, ASME Boiler and Pressure Vessel Code)

Welder Name: Peter J. Arc Check No.: 3506 Stamp No.: 506

Using WPS No.: 1 Rev.: ~ Date: 8/11/85

the above welder is qualified for the following ranges.

Variable	Record Actual Values Used in Qualification	Qualification Range
Process	GMAW	GMAW
Process Type	Semi-automatic	Semi-automatic
Backing [metal, weld metal, flux, etc. (QW-402)]	None	None
Material Spec. (QW-403)	P-1 to P-1	P-1 to P-1
Thickness		
Groove	0.562-in	All
Fillet	~	~
Diameter		
Groove	24-in	No Maximum
Fillet	~	~
Filler Metal (QW-404)		
Spec. No.	5.18	5.18
Class	ER 70S-3	ER 70S-3
F-No.	6	6
Deposited Weld Metal Thickness		
Groove X Fillet		
Position (QW-405)	2G and 5G	All position
Weld Progression	Downhill	~
Gas Type (QW-408)	CO_2	CO_2
Backing Gas (QW-408) None		
Electrical Characteristics (QW-409)		
Current	D.C.	D.C.
Polarity	Electrode +	Electrode +

Guided Bend Test Results QW-462.2(a), QW-462.3(a), QW-462.3(b)

Type and Fig. No.	Result
Side bend Q7.1	No defects
Side bend Q7.1	No defects
Side bend Q7.1	No defects
Side bend Q7.1	One minor defect
Side bend Q7.1	No defects
Side bend Q7.1	No defects

Radiographic Test Results (QW-304 & QW-305)

For alternative qualification of groove welds by radiography

Radiographic Results: None

Fillet Weld Test Results [See QW-462.4(a), QW-462.4(b)]

Fracture Test (Describe the location, nature and size of any crack or tearing of the specimen)

None

Length and Per Cent of Defects ~ inches ~ %

Macro Test—Fusion None

Appearance—Fillet Size (leg) ~ in X ~ in Convexity ~ in. or Concavity ~ in.

Test Conducted by Hobart Welding Procedure Lab Laboratory—Test No. 1065

We certify that the statements in this record are correct and that the test welds were prepared, welded and tested in accordance with the requirements of Section IX of the ASME Code.

Organization ABC Pressure Vessel Co

Date Aug 18, 1985 By Dick Bma

(Detail of record of tests are illustrative only and may be modified to conform to the type and number of tests required by the Code.)

NOTE: Any essential variables in addition to those above shall be recorded.

FIGURE 21-7 ASME record of welder qualification tests WPQ.

ing will usually have an ASME "symbol stamp." This means that the particular contractor or manufacturer has been approved by the American Society of Mechanical Engineers as an authorized manufacturer or installer of the type of equipment specified. Various stamps are used to mark the installation or the product manufactured. Some of the symbol stamps are:

- N Nuclear vessel
- PP Pressure piping
- U Pressure vessel
- S Power boilers
- H Heating boilers

To obtain an ASME symbol stamp, a manufacturer or contractor must contact the American Society of Mechanical Engineers, Boiler and Pressure Code Committee, and apply for the code symbol required. The actual mechanics are quite involved but include obtaining a contract with an authorized inspection agency, normally one of the states or provinces or a casualty insurance company. The American Society of Mechanical Engineers will advise of the exact requirements. The requirements include at least the need to prepare a written quality control manual describing a controlled manufacturing system for the scope of the proposed ASME certificates of authorization. The ASME will send a survey team to inspect your facilities and review the quality control manual and a demonstration of all items affecting quality within the scope of the certificate. This demonstration must include material control, drawings, design, inspection signoff, welding procedure specifications, welding procedure qualifications, welding performance qualifications, heat treatment, and so on. If everything is satisfactory, ASME will issue a certificate of authorization and the applicable code symbol stamp.

Structural Welding

Requirements for the AWS Structural Welding Code[6] are not as involved as the ASME Pressure Vessel Code. However "each manufacturer or contractor shall conduct the tests required by this code to qualify the welding procedures." In addition, "the engineer, at his discretion, may accept evidence of previous qualification of welders, welding operators and tackers to be employed." Thus the manufacturer or contractor is totally responsible for qualification of procedures and personnel.

AWS allows the use of prequalified welding procedures. They must conform in all respects to the provisions of the code described in a table "Mandatory Code Requirements for Pre-Qualified Joint Welding Procedures." There is an exception to the prequalified procedures, and that is if high-strength (90,000 psi) filler metals are used. By "prequalified," AWS means that they should be exempt from tests or qualifications provided that they conform in all respects to the applicable code requirements. Even so, the code requires that the manufacturer or contractor prepare a written procedure specification for the joint welding procedure to be used. This is a record of materials and welding variables which shows that the joint welding procedure meets the requirements for prequalified status. It is therefore necessary to prepare welding procedure specifications that cover the work to be done under the requirements of the AWS Structural Welding Code, D1.1.

There are other qualification requirements by AWS, and these relate to many types of weldments other than structural. To have a broader qualification record, it is best to conform to the requirements of the AWS "Standard for Welding Procedure and Performance Qualification."[2] This is because the provisions of B2.1 will fill the requirements of structural code D1.1, but also the requirements of any other welded products covered by AWS codes or specifications. In view of this, the example will describe the requirements of the Standard for Welding Procedure and Performance Qualification and utilize the forms recommended. In this example, the X,Y,Z Structural Company is qualifying a procedure for flux-cored arc welding of carbon steel using the semiautomatic method of application, and using carbon dioxide shielding gas.

For the AWS standard for welding and performance, the welding procedure is known as a welding procedure specification, and an example is shown in Figure 21-8. The information to fill in this form is essentially the same as the information used by ASME welding procedure specification.

The welding procedure specification is then qualified by making specific welds as described and testing them. An example of the AWS procedure qualification record (PQR) is shown in Figures 21-9 and 21-10. These data are also very similar to those used by the ASME procedure qualification record. One difference would be that filler metal specifications and classifications are to AWS numbers, and these numbers are all presented in the Standard B2.1.

For qualifying the welder, the AWS B2.1 uses a form called the performance qualification test record (PQTR). This is for recording the results of tests made by welders or welding operators. An example of this test record is shown in Figure 21-11. The data to be filled in are similar to ASME data. Upon completion of the tests, and if they meet the code requirements, this record is then signed by the qualifier, which qualifies the welder or welding operator. In the case of AWS, the qualification record is continuous unless no welding is done for a period of six months or if there is reason to question the ability of the welder. You must refer to the specific code or specification involved and follow it.

FIGURE 21-8 AWS welding procedure specification (WPS).

WELDING PROCEDURE SPECIFICATION (WPS)

Revision ______

Date *Nov. 12, 1985*
Company name *XYZ Structural Company Midtown U.S.A. 23456*
Supporting PQR no.(s) *2* Type - Manual ( ) Semi-Automatic (×)
Welding process(es) *FCAW* Machine ( ) Automatic ( )
Backing: Yes (×) No ( )
Backing material (type) *Steel*
Material number *M-1* Group *M-1* To material number *M-1* Group *2*
Material spec type and grade *ASTM A-441* To material spec type and grade *ASTM A-441*
Base metal thickness range Groove *1-inch* Fillet *~*
Deposited weld metal thickness range *Unlimited*
Filler metal F no. *10* A no. *1*
Spec. no. (AWS) *A5.20* Flux tradename *None*
Electrode-flux (Class) *E 70T-5* Type *~*
Consumable insert: Yes ( ) No (×) Classifications *~*
Shape *~*
Position(s) of joint *Flat (1-G) and Horzontal (2G)* Size *~*
Welding progression: Up (~) Down (~) Ferrite number (when reqd.) *~*

PREHEAT:
Preheat temp., min *None*
Interpass temp., max *~*
(continuous or special heating, where applicable, should be recorded)

GAS:
Shielding gas(es) *CO_2*
Percent composition *100%*
Flow rate *45-50 CFH*
Root shielding gas *None*
Trailing gas composition *None*
Trailing gas flow rate *None*

POSTWELD HEAT TREATMENT:
Temperature range *None*
Time range *~*

Tungsten electrode, type and size *None*
Mode of metal transfer for GMAW *N.A.* Short-circuiting ( ) Globular ( ) Spray ( )
Electrode wire feed speed range *140-175 ipm*
Stringer bead ( ) Weave bead ( ) Peening: Yes ( ) No (×)
Oscillation *As required*
Standoff distance *3/4 - 1- inch*
Multiple ( ) or single electrode (×)
Other

	Filler metal			Current				
Weld layer(s)	Process	Class	Dia	Type & polarity	Amp range	Volt range	Travel speed range	
All	*FCAW*	*E70T-5*	*3/32-in*	*D.C.+*	*400-450*	*28-30*	*10-14 ipm*	e.g., Remarks, comments, hot wire addition, technique, torch angle, etc.

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Approved for Production by *Henry Roe*
Employer

Note Those items that are not applicable should be marked N.A

FIGURE 21-9 AWS procedure qualification record (PQR), sheet 1.

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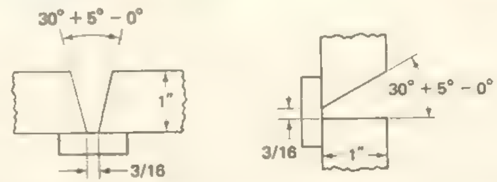
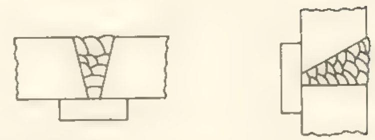
PROCEDURE QUALIFICATION RECORD (PQR)

Welding process *F.C.A.W.*
Company *XYZ Structural Company* Equipment type and model (sw) *~*

JOINT DESIGN USED



WELD INCREMENT SEQUENCE



Single (×) Double weld ( )
Backing material *Steel*
Root opening *3/16-in* Root face dimension *0*
Groove angle *30°+5°-0°* Radius (J-U) *None*
Back gouging: Yes ( ) No (×) Method *~*

BASE METALS
Material spec *A-441* To *A-441*
Type or grade *~* To *~*
Material no *M-1* To material no *M-1*
Group no *2* To group no *2*
Thickness *1-inch*
Diameter (pipe) *N.A.*
Surfacing: Material *N.A.* Thickness *~*
Chemical composition *~*
Other *~*

FILLER METALS
Weld metal analysis A no *1*
Filler metal F no *10*
AWS specification *A5.20*
AWS classification *E 70T-5*
Flux class *None* Flux brand *~*
Consumable insert: Spec. *~* Class. *~*
Supplemental filler metal spec. *~* Class. *~*
Non-classified filler metals *~*
Consumable guide (ESW) Yes (~) No (~)
Supplemental deoxidant (EBW) *~*

POSITION
Position of groove *F and H* Fillet *~*
Vertical progression: Up (~) Down (~)

PREHEAT
Preheat temp., actual min *None*
Interpass temp., actual max *~*

POSTWELD HEAT TREATMENT:
Temp. *None*
Time *~*
Other *~*

GAS
Gas type(s) *CO_2*
Gas mixture percentage *100%*
Flow rate *30-35 CFH*
Backing gas *None* Flow rate *~*
Root shielding gas *None*
EBW vacuum (~) Absolute pressure (~)

ELECTRICAL CHARACTERISTICS
Electrode extension *5/8 - 3/4 - inch*
Standoff distance *1 inch*
Transfer mode (GMAW) *~*
Electrode diameter tungsten *None*
Type tungsten electrode *~*
Current: AC ( ) DCEP (x) DCEN ( ) Pulsed ( )
Heat input *~*
EBW beam focus current *~* Pulse freq. *~*
Filament type *~* Shape *~* Size *~*
Other *~*

TECHNIQUE
Oscillation frequency *~* Weave width *~*
Dwell time *Oscillation as required*
String or weave bead *~* Weave width *~*
Multi-pass or single pass (per side) *Multi-pass*
Number of electrodes *One*
Peening *None*
Electrode spacing *~*
Arc timing (SW) *~* Lift (~)
PAW: Conventional (~) Key hole (~)
Interpass cleaning: *Yes*

Pass no.	Filler metal size	Amps	Volts	Travel speed (ipm)	Filler metal wire (ipm)	Slope induction	Special notes (process, etc.)
All	*3/32-in*	*400-450*	*28-30*	*10-14*	*140-175*	*N.A.*	*~*

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Note: Those items that are not applicable should be marked N.A.

FIGURE 21-10 AWS procedure qualification record (PQR), sheet 2.

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PQR No.2

TENSILE TEST SPECIMENS: PROCEDURE QUALIFICATION RECORD

Type: Reduced Section Tensile specimen size: 1x3/4-inch Area: 3/4 sq. in.

Groove (x) Reinforcing bar (~) Stud welds (~)

Tensile test results: (Minimum required UTS 62,000 psi)

	Specimen no.	Width, in.	Thickness, in.	Area, in.^{2}	Max load lbs	UTS, psi	Type failure and location
F	M-8751-C1	0.990	0.746	0.7376	56,700	76,870	Base Metal
	M-8751-C2	0.994	0.746	0.7415	57,275	77,240	Base Metal
H	M-8751-E1	0.991	0.790	0.7829	68,000	87,000	Base Metal
	M-8751-E2	0.993	0.789	0.7835	69,850	89,150	Base Metal

GUIDED BEND TEST SPECIMENS - SPECIMEN SIZE: 3/8 x 1-inch

(Flat) Type	Result	(Horizontal) Type	Result
Side bend	Passed	Side bend	Passed
Side bend	Passed	Side bend	Passed

MACRO-EXAMINATION RESULTS:

None

Reinforcing bar (~)
1. ~
2. ~
3. ~

Stud (~)
4. ~
5. ~

SHEAR TEST RESULTS - FILLETS:

None

1. ~
2. ~
3. ~
4. ~

IMPACT TEST SPECIMENS

Type: Charley V-notch Size: 10 mm x 10 mm

Test temperature: −20°F, −40°F, −60°F, −80°F

Specimen location: WM = weld metal; BM = base metal; HAZ = heat-affected zone

Test results

Welding position	Specimen location	Energy absorbed (ft.-lbs.)	Ductile fracture area (percent)	Lateral expansion (mils)
Flat	WM	95	100	80
Flat	WM	82	100	76
Flat	WM	65	100	70
Flat	WM	50	100	50

IF APPLICABLE — **RESULTS**

Hardness tests: (~) Values ~	Acceptable ( )	Unacceptable ( )
Visual (special weldments 2.4.2) (~)	Acceptable ( )	Unacceptable ( )
Torque (~) psi	Acceptable ( )	Unacceptable ( )
Proof test (~) Method	Acceptable ( )	Unacceptable ( )
Chemical analysis (~)	Acceptable ( )	Unacceptable ( )
Non-destructive exam (~) Process	Acceptable ( )	Unacceptable ( )
Other None.	Acceptable ( )	Unacceptable ( )

Mechanical Testing by (Company) ~ Lab No. TWB-707-C

We certify that the statements in this Record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of the American Welding Society Standard for Welding Procedure and Performance Qualification (AWS B2.1-83).

Qualifier: XYZ Structural Company Reviewed by: John Jones

Date: Nov. 12, 1985 Approved by: Tom Brown

Employer

FIGURE 21-11 AWS performance qualification test record.

PERFORMANCE QUALIFICATION TEST RECORD

Name John Doe Identification TWB-707-C Welder (x) Operator ( )

Social security number: 123-45-4321 Qualified to WPS no. 200

Process(es) FCAW Manual ( ) Semi-Automatic (x) Automatic ( ) Machine ( )

Test base metal specification ASTM A-441 To ASTM A-441

Material number M-1 To M-1

Fuel gas (OFW) None

AWS filler metal classification A5.20 E 70T-5 F no. 10

Backing: Yes (x) No ( ) Double ( ) or Single side (x)

Current: AC ( ) DC (x) Short-circuiting arc (GMAW) Yes ( ) No ( )

Consumable insert: Yes ( ) No (x)

Root shielding: Yes ( ) No (x)

TEST WELDMENT — **POSITION TESTED** — **WELDMENT THICKNESS (T)**

GROOVE:

Pipe 1G ( ) 2G ( ) 5G ( ) 6G ( ) 6GR ( ) Diameter(s) ~ (T)

Plate 1G (x) 2G (x) 3G ( ) 4G ( ) (T) 1-inch

Rebar 1G ( ) 2G ( ) 3G ( ) 4G ( ) Bar size ~ Butt ( ) Spliced butt ( )

FILLET:

Pipe ( ) 1F ( ) 2F ( ) 3F ( ) 4F ( ) 5F ( ) Diameter (T)

Plate ( ) 1F ( ) 2F ( ) 3F ( ) 4F ( ) (T)

Other (describe) ~

Test results: Remarks

Visual test results	N/A (x)	Pass ( )	Fail ( )
Bend test results	N/A ( )	Pass (x)	Fail ( )
Macro test results	N/A (x)	Pass ( )	Fail ( )
Tension test	N/A ( )	Pass (x)	Fail ( )
Radiographic test results	N/A (x)	Pass ( )	Fail ( )
Penetrant test	N/A (x)	Pass ( )	Fail ( )

QUALIFIED FOR:

PROCESSES

GROOVE: — **THICKNESS**

Pipe 1G ( ) 2G ( ) 5G ( ) 6G ( ) 6GR ( ) (T) Min Max Dia

Plate 1G (x) 2G (x) 3G ( ) 4G ( ) (T) Min 3/16 Max Unlimited

Rebar 1G ( ) 2G ( ) 3G ( ) 4G ( ) Bar size Min Max

FILLET:

Pipe 1F ( ) 2F ( ) 4F ( ) 5F ( ) (T) Min Max

Plate 1F ( ) 2F ( ) 3F ( ) 4F ( ) (T) Min 3/8 Max No Max

Rebar 1F ( ) 2F ( ) 3F ( ) 4F ( ) Bar size Min Max

Weld cladding ( ) Position(s) T Min Max Clad Min

Consumable insert ( ) Backing type ( )

Vertical Up ( ) Down ( )

Single side ( ) Double side ( ) No backing ( )

Short-circuiting arc ( ) Spray arc ( ) Pulsed arc ( )

Reinforcing bar - butt ( ) or Spliced butt ( )

The above named person is qualified for the welding process(es) used in this test within the limits of essential variables including materials and filler metal variables of the AWS Standard for Welding Procedure and Performance Qualification (AWS B2.1)

Date tested Nov. 12, 1985 Signed by Tom Brown

Qualifier

Cross-Country Pipelines

The API Standard 1104[38] for welding pipelines and related facilities requires procedure and welder qualification. This code was designed so that qualification tests can be made in the field. It is used worldwide. The procedure specification includes the process, the base metal material, the size of pipe, diameter and wall thickness, the joint detail, the filler metal type, size and number of passes, and the electrical characteristics utilized. For gas welding, the flame characteristics, direction of welding, welding position, type of flux, and so on, must be made known. If any of the essential variables are changed, the welding procedure must be reestablished and completely requalified. This includes a change in the welding process, a change in the pipe material or size, a change in the joint design, a change in the position, a change in filler metal, a change in filler metal size, and so on. These changes are described in detail. The code must be referred to in writing a qualified welding procedure. An example of an API qualified welding procedure is given in Figures 21-12 to 21-14. These illustrations utilize the API forms found in the code.

Other codes may reference the three codes just described, and in these cases the same provisions would apply. It must be reemphasized that the code in question must be studied in order to write an intelligent welding procedure and qualify it.

F.G.H. Cross Country Pipe Line Co

STANDARD PROCEDURE SPECIFICATION NO. 3

For SMAW Welding of X-52 Pipe and Fittings   Date - 11.30.82 Sheet 1 of 3

A. Process: Shielded Metal Arc Welding

B. Material: A.P.I. Std. Line Pipe X-52

C. Diameter and Wall Thickness: 4½" to 12¾" by 3/16" to 3/4"

D. Joint Design: Single Vee Groove 60° to 75° 1/16 RO + 1/16 RF

E. Filler Metal and Number of Beads: See Sketch and Schedule

F. Electrical or Flame Characteristics: D.C. Electrode Positive

G. Position: Horizontal Fixed - 5G

H. Direction of Welding: Downhill

I. Number of Welders: One

J. Time Lapse between Passes: Unlimited

K. Type of Line-up Clamp: None

L. Removal of Line-up Clamp: Not required

M. Cleaning: Mechnical to Remove all Slag

N. Preheat, Stress Relief: None

O. Shielding Gas and Flow Rate: None

P. Shielding Flux: None

Q. Speed of Travel: Total Time for Joint 23 min

R. Sketches and Tabulations (to be attached) See Sheet 2 of 3

Tested.   Welder: P L. Welder

Approved: Welding Sup.: W. S. Jones

Adopted: Chief Engineer: C. E Smith

FIGURE 21-12 API standard procedure specification: data sheet.

FIGURE 21-13 API standard procedure specification: sketches and tabulation.

F G H Cross Country Pipe Line

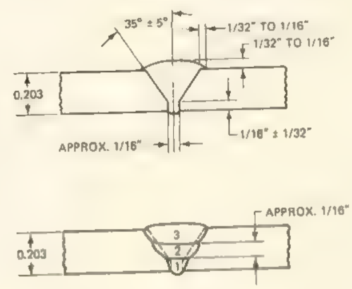
STANDARD PROCEDURE SPECIFICATIONS

SKETCHES & TABULATIONS

Spec No 3

Date 10-30-82

Sheet 2 of 3



ELECTRODE SIZE & NUMBERS OF BEADS

NUMBER OF BEADS

PIPE WALL THICKNESS	ELECTRODE	ELECTRODE	ELECTRODE	TOTAL NUMBER OF BEADS
0.203"	1-1/8" E6010	1-1/8" E7010	1-5/32" E7010	3

NOTE: FIRST PASS ONLY E6010
REMAINING PASSES USE E 7010
COVER BEAD MAY BE MADE WITH E7010

VOLTAGE & AMPERAGE RANGE

ELECTRODE DIAMETER	AMPERAGE	ARC VOLTS
1/8" E6010	110	27
1/8" E 7010	110	27
5/32" E 7010	130	26

F.G.H. Cross Country Pipe Co

COUPON TEST REPORT

Test No T242

Location Troy, Ohio
Date 11 30 85 State Roll Weld No. Fixed position Weld Yes
Welder John C Hickman Mark 3509
Welding time 23 mins Time of day 10.00 AM M. Temperature 70°F
Weather condition Welding was done indoors
Wind break used None voltage 25 – 28 amperage 110 – 130
Type of welding machine Hobart DC Gen. Size 300 Amp
Filler metal Hobart # 10, Hobart # 885
Size of reinforcement 1/32 to 1/16
Pipe Kind and Grade 5LX X-52
Wall thickness 203 Dia O.D 8"

	1	2	3	4	5	6	7
Bead No							
Size of Electrode	1/8	1/8					
No of Electrode	4	3					

	1	2	3	4	5	6	7
Coupon stenciled	1	2					
Original	0 937	1 015					
Dimension of plate	0 203	0 203					
Orign area of plate	0 190	0 206					
Maximum load	15,200	16,300					
Tensile S/in plate area	80,000	79,200					
Fracture location	Base Metal	Base Metal					

☒ Procedure ☒ Qualifying Test ☒ Qualified
☐ Welder ☐ Line Test ☐ Disqualified

Max tensile 80,000 Min tensile 79,200 Avg. tensile 79,500

Remarks on tensile
1. Failed in base metal 2" from weld
2. Failed in base metal 1-1/2" from weld
3.
4

Remarks on Bend Tests
1. Root bend, no defects, passed
2. Root bend, one minor defect, passed
3. Face bend, no defects, passed
4. Face bend, minor defects, passed

Remarks on Nick Tests
1. No defects
2. No defects
3.
4

Test made at Hobart Technical Center Date 11.23.85
Tested by Supervised by

FIGURE 21-14 API standard procedure specification: coupon test report.

21-4 STANDARD WELDING PROCEDURE SPECIFICATIONS

A major expense of welding fabricators, contractors, construction companies, and weldment manufacturers is the necessity to design, write, prepare, test, and qualify welding procedures. This expense becomes excessive because of the necessity of requalifying the same procedures and personnel over and over. The requalification of welding procedures and welders is due to code requirements, customer requirements, or legal reasons.

Welding companies are required to have qualified welding procedures for welding similar or different metals together in different thickness ranges using different welding processes and welding filler materials. This involves different joint details, welding positions, metal products, and joint welding techniques. Many companies have hundreds of qualified welding procedures to enable them to manufacture their products.

The use of standard welding procedure specifications can greatly reduce this expense. The standard welding procedure specifications will satisfy all of the technical requirements of most welding codes and specifications. A standard welding procedure specification (Std. WPS) would list ranges of all variables acceptable for the application of the particular specification. Each standard WPS is based on data from hundreds of proven procedure qualification records (PQRs) and/or extensive tests. These provide directions for making acceptable welds with specific processes on specific metals, and so on, by a skilled welder or welding operator. The standard welding procedure specifications have a broader technical base than those normally qualified by a single organization. They are supported by more test data, including the results from research programs

The standard procedure specifications will provide ranges of the welding variables that will be practical for the applications for which they are to be used. These will be narrow enough so that acceptable welds can be made at the extremities of the ranges.

The standard welding procedure specifications are permitted to be used on work covered by the code or specification for which it has been approved. They do not require further testing or qualification work by the welding company. Thus it will no longer be necessary for the welding company to develop and qualify specific welding procedures specifications. However, new welding processes, materials, or filler metals must still be tested and qualified as in the past.

The standard WPS do not replace the applicable code or standard. They merely replace individual company's own WPSs and PQRs. Standard welding procedure specifications will still require engineering judgment so that the ranges of variables are suitable for the application.

The standard welding procedure specifications are approved by the American Welding Society and by the American National Standards Institute (ANSI). They would also be approved by the code- or specification-writing organization.

The standard welding procedure specifications adopted so far are shown by Figure 21-15. All standard welding procedure specifications will follow a standardized format similar to AWS and ASME forms. They will use filler metal and base metal specifications used by existing codes and specifications. The Standardized Welding Procedure Specifications can be obtained from the American Welding Society, Miami, Florida. It is anticipated that the standard WPSs will save the welding industry tremendous sums of money and may enable them to become more competitive throughout the world.

Standard WPS Number	Welding Process	Process Variation	Application Method	Base Metal	Position	Miscellaneous Information
001	SMAW	—	M.A.	Carbon steel	All	$\frac{3}{16}$–$\frac{3}{4}$-in.-thick L.H.
002	GTAW	—	M.A.	Carbon steel	All	$\frac{3}{16}$–$\frac{3}{8}$-in.-thick—argon dc
003	GMAW	Short circuiting	S.A.	Galvanized steel	All	Sheet metal—argon + CO_2
004	GMAW	Short circuiting	S.A.	Carbon steel	All	Sheet metal—argon + CO_2
005	GMAW	Short circuiting	S.A.	Austenitic SS	All	Sheet metal 90% He, 7% argon, 2% CO_2
006	GMAW	Short circuiting	S.A.	CS to austenitic SS	All	Sheet metal 90% He, 7% argon, 2% CO^2
007	GTAW	—	M.A.	Galvanized steel	All	Sheet metal—argon
008	GTAW	—	M.A.	Carbon steel	All	Sheet metal—argon
009	GTAW	—	M.A.	Austenitic SS	All	Sheet metal—argon
010	GTAW	—	M.A.	CS to austenitic SS	All	Sheet metal—argon

FIGURE 21-15 Standard welding procedure specifications.

QUESTIONS

21-1. What are the three components of a welding manufacturing system?

21-2. What is the purpose of a procedure qualification record (PQR)?

21-3. What is the purpose of a welder performance qualification (WPQ) test?

21-4. Why are perfect welds required for some classes of work and not others?

21-5. Who is responsible for a good-quality product?

21-6. Who is responsible for a good-quality weld?

21-7. There are 20 factors included in a quality assurance plan. Name as many as you can.

21-8. Codes and specifications are related to industries. What industries use welding specifications?

21-9. What is a welding procedure specification (WPS)?

21-10. What is a welding procedure? Name two types.

21-11. Is the ASME Section IX, welding qualifications, enforceable by law?

21-12. Can welders be certified by a contractors' association? Who does this, and how?

21-13. What is an ASME symbol stamp? Who can use it?

21-14. What welded products are covered by the AWS structural code? What materials?

21-15. What are prequalified welding processes? Explain.

21-16. What welded products are covered by API Standard 1104?

21-17. How are automatic welding equipment and operators qualified?

21-18. What method does API 1104 use for fracture toughness testing?

21-19. How will standard WPSs reduce the cost of weldments?

21-20. Who makes standard welding procedure specifications available to the industry?

REFERENCES

1. Howard Woodward, "The Importance of a Welding Manufacturing System," *Welding Journal*, Sept. 1986.
2. "Standard for Welding Procedure and Performance Qualification," AWS B2.1, American Welding Society, Miami, Fla.
3. "Boiler and Pressure Vessel Code," American Society of Mechanical Engineers, New York.
4. "Code of Federal Regulations," Section 10, Energy Part 50, Appendix B (10CFR50-B), Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants.
5. "Standard for Welding of Reactor Coolant and Associated Systems and Components for Navel Nuclear Power Plants," Navships 250-1500-1.

6. "Structural Welding Code," AWS D1.1, American Welding Society, Miami, Fla.
7. "Standard Specifications for Highway Bridges," American Association of State Highway Officials, Washington, D.C.
8. "Specifications for Steel Railway Bridges," American Railway Engineering Association, Chicago, 1969.
9. U.S. Coast Guard, Department of Transportation, "Marine Engineering Regulations," Sub Chapter F, Part 57, "Welding and Brazing," Code of Federal Regulations, Washington, D.C.
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13. "Guide for Steel Hull Welding," AWS D3.5, American Welding Society, Miami, Fla.
14. "Guide for Aluminum Hull Welding," AWS D3.7, American Welding Society, Miami, Fla.
15. "Standard for Welded Steel Elevated Tanks, Standpipes and Reservoirs for Water Storage," AWS D5.2, American Welding Society, Miami, Fla.
16. "Standard for Welded Steel Tanks for Oil Storage," API Standard 650, American Petroleum Institute, Washington, D.C.
17. "Specifications for Tank Cars," Association of American Railroads, Washington, D.C.
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22. "Aerospace Material Specifications," Society of Automotive Engineers, Warrendale, Pa.
23. "National Aerospace Standards," Aerospace Industries Association of America, Washington, D.C.
24. "Qualification of Aircraft, Missile and Aerospace Fusion Welders," Military Standard MIL-T-1595A, Department of Defense, Washington, D.C.
25. "Welding on Earthmoving and Construction Equipment," AWS D14.3, American Welding Society, Miami, Fla.
26. "Welding Industrial and Mill Cranes," AWS D14.1, American Welding Society, Miami, FLa.
27. "Metal Cutting Machine Tool Weldments," AWS D14.2, American Welding Society, Miami, Fla.
28. "Specifications for Welding of Presses and Press Components," AWS D14.5, American Welding Society, Miami, Fla.
29. "Specifications for Rotating Elements of Equipment," AWS D14.6, American Welding Society, Miami, Fla.
30. "Classification and Application of Welded Joints for Machinery and Equipment," AWS D14.4, American Welding Society, Miami, Fla.
31. "Recommended Practices for Automotive Welding Design," AWS D8.4, American Welding Society, Miami, Fla.
32. "Recommended Practices for Automotive Portable Gun-Resistance Spot Welding," AWS D8.5, American Welding Society, Miami, Fla.
33. "Standard for Automotive Resistance Spot Welding Electrodes," AWS D8.6, American Welding Society, Miami, Fla.
34. "Specifications for Automotive Welding Quality—Resistance Spot Welding," AWS D8.7, American Welding Society, Miami, Fla.
35. "Specifications for Automotive Frame Weld Quality—Arc Welding," AWS D8.8, American Welding Society, Miami, Fla.
36. "Standard for Welding Procedure and Performance Qualifications," AWS B2.1, American Welding Society, Miami, Fla.
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22

Weldment Evaluation and Quality Control

OUTLINE

22-1 DESTRUCTIVE TESTING

Welds and weld metal are probably subjected to more different types of tests than any other metal produced. Weld metal can be tested in the same manner as any other form of metal. Mechanical tests are used to qualify welding procedures, welders, welding processes and to determine if electrodes and filler metals meet the requirements of the specification. Welds in weldments are often tested for soundness, strength, and toughness by means of mechanical tests.

Mechanical tests are destructive tests since the weldment or weld joint is destroyed in making the test specimen. They are also expensive since they involve preparation of material, making welds, cutting and often machining weld test specimens, and finally mechanical or destructive testing these specimens.

Procedure Qualification

To qualify a welding procedure specification (WPS) you must make specific welds, cut them into standardized sizes and shapes, and test them to destruction. These tests are

spelled out in detail by the specification being followed.

The purpose of the procedure qualification test is to prove that a weld made under prescribed conditions will provide the necessary mechanical properties. This involves making test plates according to the welding procedure specification and then testing the weld by mechanical means. The welding process, filler metals, and the welding schedule are selected to make the weld in the position required on the base metal that is to be used. Welding joint details and material thickness may be specified and may not be exactly as will be utilized in making the production weldment. Requirements vary from code to code and it is therefore essential that the code be studied when making the test welds. The different codes may have different requirements and the test specimens are not always exactly the same, nor are they taken from the same positions of a test plate. In general, the codes utilize the same type of weld specimens, including the fillet break test, the nick break test, the tensile test, and the guided bend test. It is essential that the latest edition of the code or specification in question be checked when making test welds, test specimens, and the tests of the weld. This is doubly important since both procedure qualification and welder qualification tests are involved.

The American Petroleum Institute standard 1104, "Standard for Welding Pipeline and Related Facilities," is extremely popular and used for much of the field pipe welding. The important thing about this code is that the test specimens must be taken from the test weld pipe in the proper location. Figure 22-1 shows the location of test specimens based on the size of pipe. It also indicates the number of test specimens that should be taken. The detail of the nick break test specimen is shown in Figure 22-2. The bend test specimens are shown in Figures 22-3 and 22-4. Note that root and face bend specimens are used for thinner material and the side bend specimen is used when the wall thickness of the pipe is over ⅜ in. (9.5 mm).

The API tests are often made in field locations and for this reason it is permissible to use flame-cut edges and grinding to prepare specimens. This eliminates all machining operations and makes it possible to quickly prepare test specimens and to make tests, in the field, with a portable bend test machine. The basis for acceptance of the test welds is spelled out in detail in the code.

The American Society of Mechanical Engineers Boiler and Pressure Vessel Code Section IX, "Welding and Brazing Qualifications," is widely used for pressure vessel work and is the reference specification for pressure piping work. This code is more complex than the API standard 1104, because it covers more types of metals and welding processes. This code makes use of the guided bend test and the fillet weld test. The fillet weld performance test is similar to the AWS test. The ASME requires reduced section tensile test for certain requirements. The

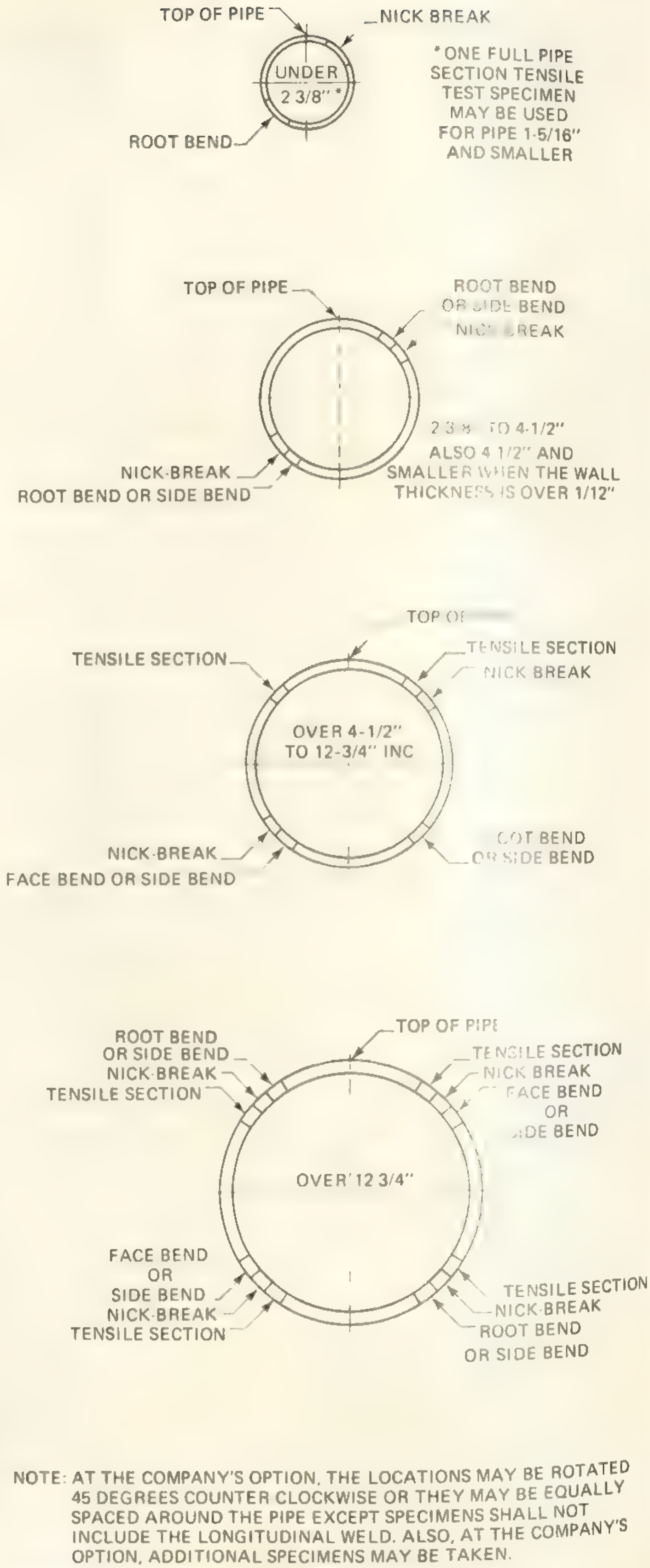


FIGURE 22-1 API test specimen locations.

location of test specimens and the details of them are shown in the code. For the guided bend test, special dimensions are provided for different thicknesses of test specimens. The American Welding Society's "Structural Welding Code," D1.1, is very popular and widely used for qualifying procedures and welders. One of the tests from the structural code, which is often used for preliminary evaluation, is the fillet weld break specimen used for qualifying weld tackers. This specimen, and the way it is fractured is shown in Figure 22-5. According to AWS code, the thickness of the plates shall be ½ in. (12.6 mm) and the fillet weld should be ¼ in. (6.3 mm). Variations of this specimen use thinner plates and smaller fillet sizes. This specimen can be used for each welding position and can be used for all of the arc welding processes and any electrode type.

The structural code includes another fillet test that has been used for welder qualification. In this test, fillet welds are made between two plates and a backing bar. The plates are separated $^{15}/_{16}$ in. (24 mm), and the fillet welds are made between each plate and the backing bar. The remaining area between the fillet welds is filled in like a groove weld. The difficulty with this test is that the backing bar must be removed for testing and this requires machining. This specimen can be tested with the

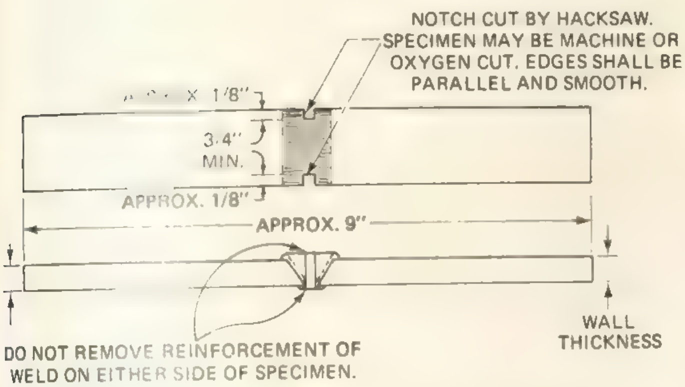


FIGURE 22-2 API code nick break test specimen.

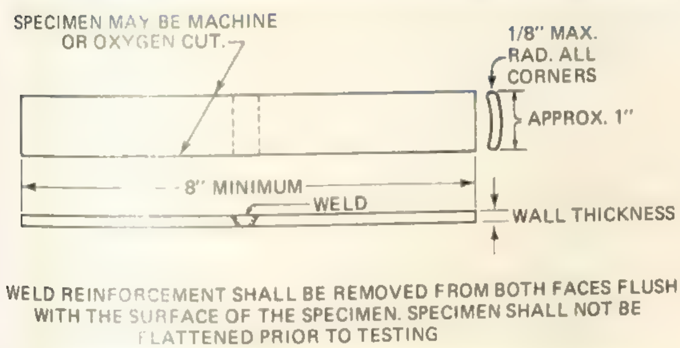


FIGURE 22-3 API code root and face bend specimen.

FIGURE 22-4 API code root bend specimen.

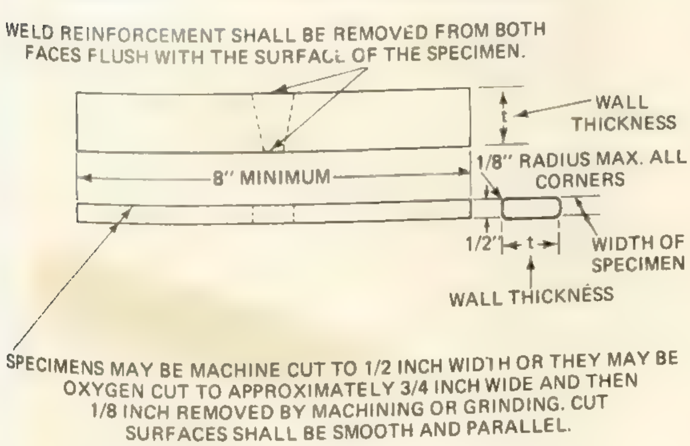
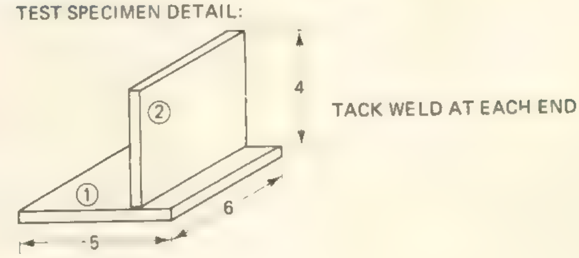


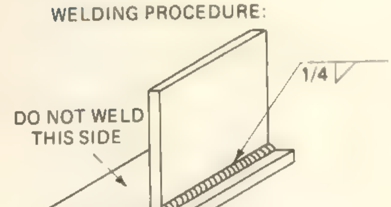
FIGURE 22-5 AWS fillet break test.

TEST SPECIMEN DETAIL:



BILL OF MATERIAL
Item 1 – 1 piece 3/8 x 5 x 6 Mild Steel – ASTM A-37
Item 2 – 1 piece 3/8 x 4 x 6 Mild Steel – ASTM A-37

WELDING PROCEDURE:



Position	Electrode size (in)	Fillet size (in)
Flat	3/16	1/4
Horizontal	3/16	1/4
Vertical	5/32	1/4 and 3/8
Overhead	5/32	1/4 and 3/8

TEST BAR PREPARATION: None

TEST SPECIFIED

STANDARD OF ACCEPTABILITY:
(a) Contour—The exposed face of the weld shall be reasonably smooth and regular. There shall be no overlapping or undercutting. The weld shall conform to the required cross section for the size of weld specified per gage.
(b) Extent of Fusion—There shall be complete fusion between the weld and base metal and full penetration to the root of the weld.
(c) Soundness—The weld shall contain no gas pocket, oxide particle or slag inclusion exceeding 3/32 in. in greatest dimension. In addition, no square inch of weld metal area shall contain more than 6 gas pockets exceeding 1/16 inch in greatest dimension.

root in tension, or the face in tension. This test can be very critical when it is tested with the root in tension, since this shows root penetration of the fillets. The details of this test are shown in Figure 22-6. The examination of this test and the requirements are listed in the code. For welder qualification, the code also provides for groove weld test specimens. The weld joint detail is a single V-groove weld with a 45° included angle and a ¼-in. (6.3 mm) root opening. A backup bar is used. The specimen can be welded in different positions. However, when it is used in the horizontal position, it is usually a single bevel weld with the bottom horizontal and the 45° bevel on the top piece. These specimens are shown in Figure 22-7. These specimens are then cut and given a guided bend test. For plate heavier than ⅜ in. (9.5 mm) the side bend specimen is required. Since different strength level materials have different bending characteristics, the design detail of the guided bend fixture is altered. The details of the guided bend fixture are shown in Figure 22-8. Testing a specimen in a guided bend fixture is shown in Figure 22-9.

Other destructive tests are required for other reasons. For example, to check the compliance of deposited weld metal, a special joint design and *all-weld* metal test specimen is required. This joint design and test specimen are specified in the various filler metal specifications of the American Welding Society. Figure 22-10 shows the joint detail for making *all-weld* metal test specimens. In many cases impact properties are also specified on a particular filler metal. When this is so, impact test specimens must also be made and they are made with the same joint detail as shown in Figure 22-10. The detail of the *all-weld* metal test specimen Type 505 is shown in Figure 22-11 and the detail of the Charpy vee notch impact test specimen is shown in Figure 22-12. These test specimens are universally used and the detail dimensions of them are identical in most specifications.

There are several other weld test specimens that may be used, including the transverse fillet weld specimen, (Figure 22-13) and the longitudinal fillet weld shear specimen (Figure 22-14). Many other weld specimens are used for development and research work. For further information refer to the AWS "Standard Method of Mechanical Testing of Welds."[1] This document shows the detail dimensions of many weld specimens in addition to these.

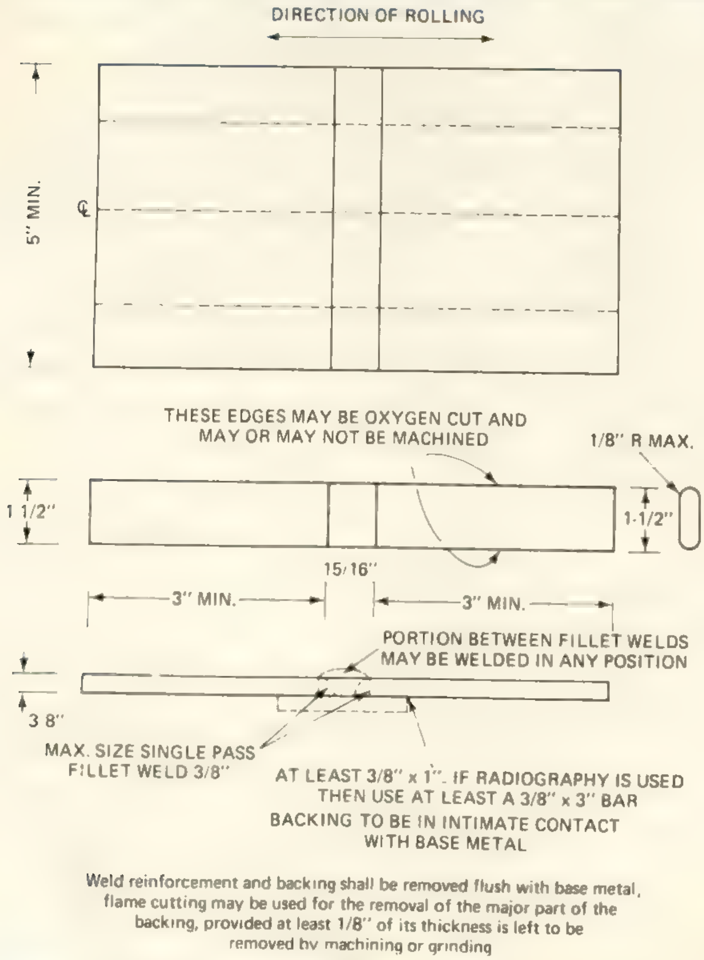
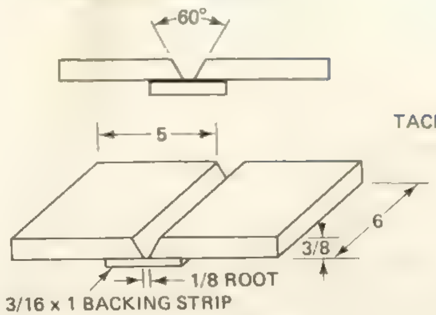


FIGURE 22-6 AWS fillet weld root bend test.

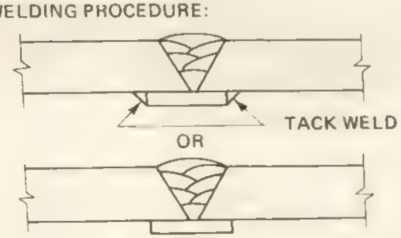
FIGURE 22-7 **AWS groove weld.**

TEST SPECIMEN DETAIL:



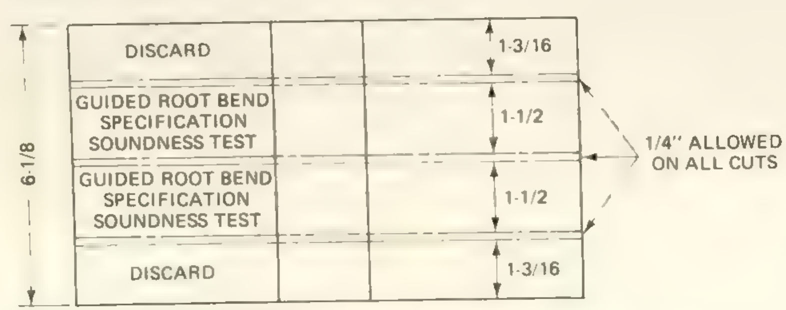
BILL OF MATERIAL: 2 pieces 5 × 6 × 3/8 and 1 piece 1 × 3/16 Mild Steel

WELDING PROCEDURE:



Position	Electrode size (in)	No. of Passes
Horizontal	1/8	6 to 7
Vertical	1/8	6 to 7
Overhead	1/8	6 to 7

TEST BAR PREPARATION:



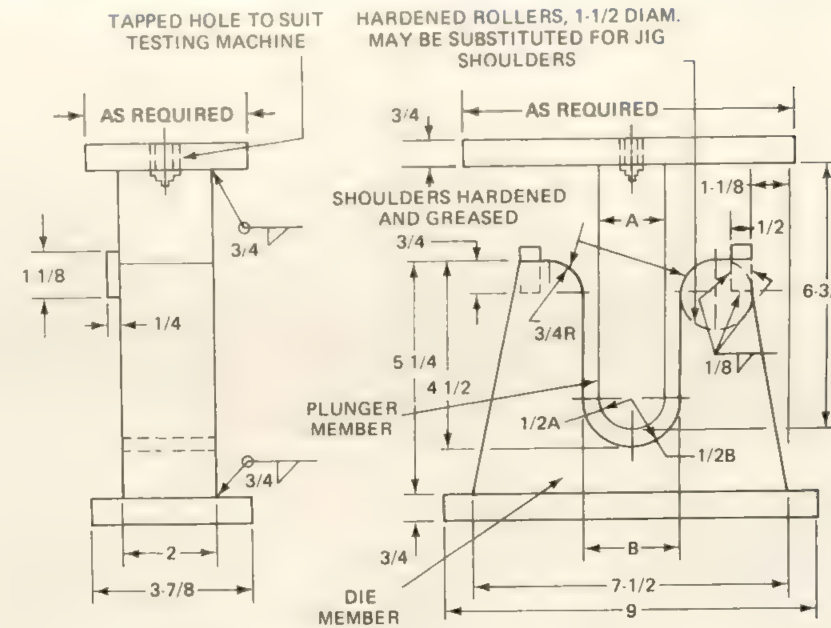
STANDARD OF ACCEPTABILITY:

(a) Contour—The exposed face of the weld shall be reasonably smooth and regular. There shall be no overlapping or undercutting.

(b) Extent of Fusion—There shall be complete fusion between the weld and base metal and full penetration to the root of the weld.

(c) Soundness—The weld shall contain no gas pocket, oxide particle or slag inclusion exceeding 1/8" in greatest dimension. In addition, no square inch of weld metal area shall contain more than 6 gas pockets exceeding 1/16" in greatest dimension.

FIGURE 22-8 **AWS guided bend test jig.**



THICKNESS OF SPECIMEN	A	B
3/8	1-1/2	2-3/8
1	4t	6t + 1/8

ALL DIMENSIONS ARE IN INCHES.

NOTES:

1. The ram shall be fitted with an appropriate base and provision for attachment to the testing machine. The ram shall also be designed to minimize deflection and misalignment.
2. The specimen shall be forced into the die by applying the load on the plunger until the curvature of the specimen is such that a 1/8 in. (3.2 mm) diam. wire cannot be placed between the specimen and any point in the curvature of the plunger member of the jig.

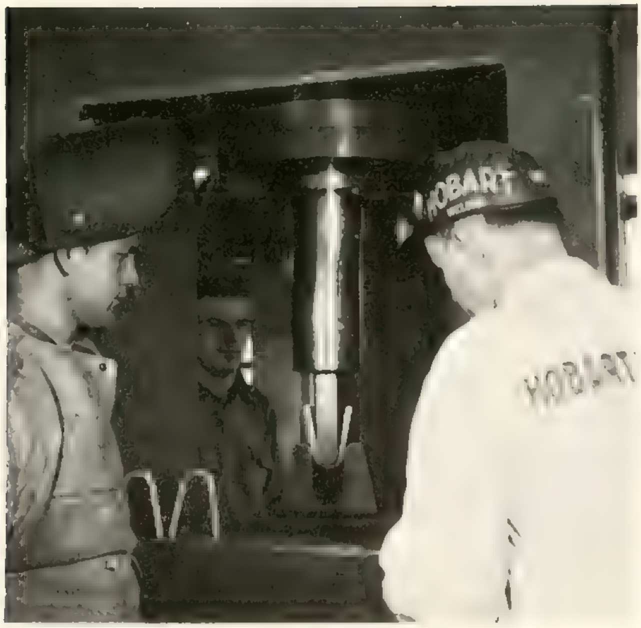


FIGURE 22-9 Making a guided bend test.

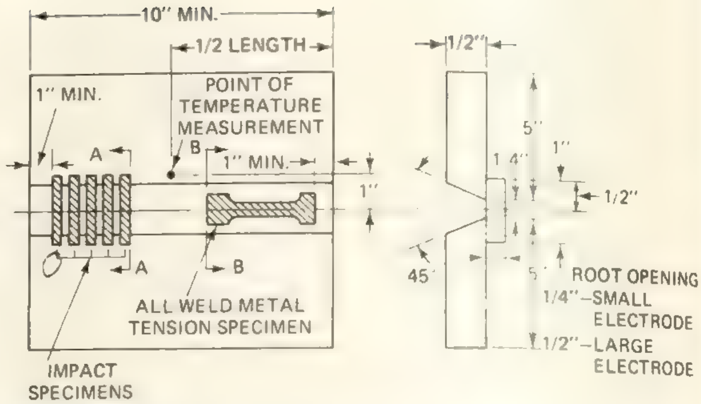


FIGURE 22-10 AWS all weld metal test.

FIGURE 22-11 Tensile test specimen: 505.

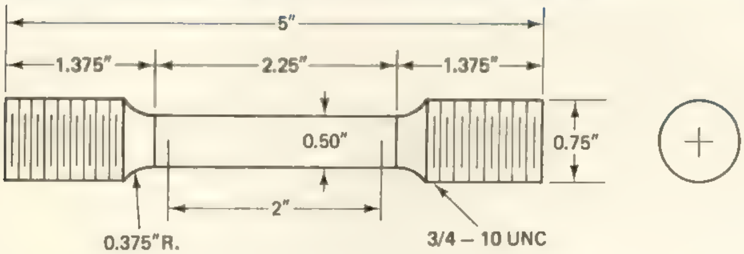
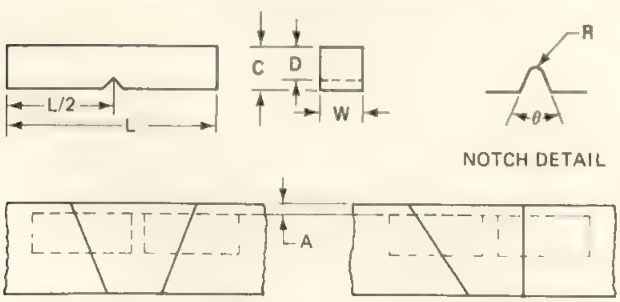
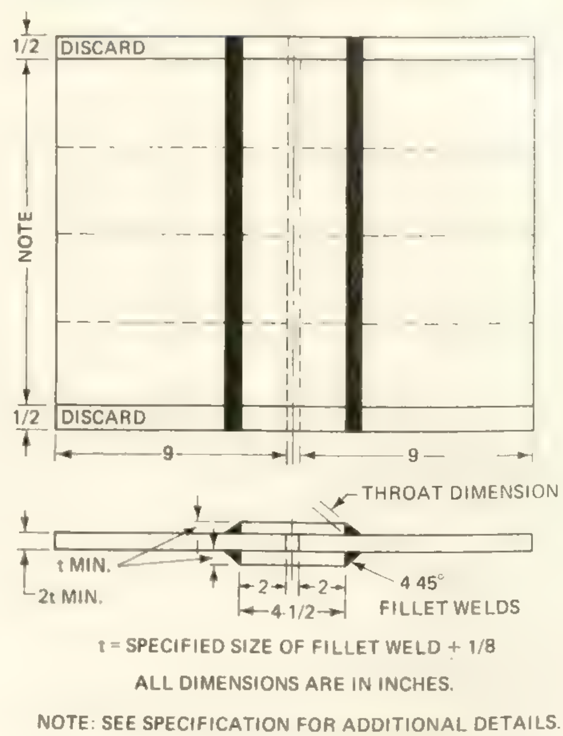


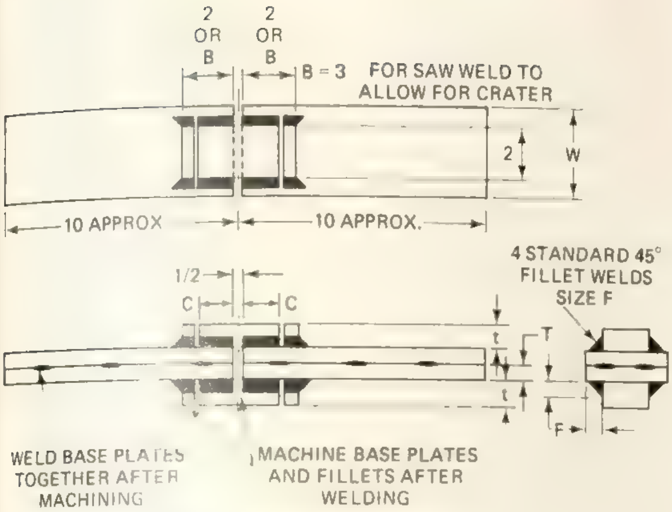
FIGURE 22-12 Impact test specimen: Charpy V notch.



Dimension	in.	mm
A–Distance of sample below specimen	0.06 ± 0.002	1.6 ± 0.05 – 0
L–Length of specimen	2.165 ± 0.002	55.0 ± 0, –2.5
L/2–Location of notch	1.082 ± 0.002	27.5 + 1.0
C–Cross section (depth)	0.394 ± 0.001	10.000 ± 0.025
W–Cross section (width)	0.394 ± 0.001	10.000 ± 0.025
D–Bottom of notch to base	0.315 ± 0.001	8.000 ± 0.025
R–Radius of notch	0.010 ± 0.001	0.250 ± 0.025
θ–Angle of notch 45 deg ± 1 deg	Adjacent sides shall be 90 deg ± 10 minutes	

FIGURE 22-13 Transverse fillet weld test.





ALL DIMENSIONS ARE IN INCHES.

DIMENSION	IN	MM
SIZE OF WELD, F	1/8	3.2
	1/4	6.4
	3/8	9.5
	1/2	12.7
THICKNESS, t, MIN	3/8	9.5
	1/2	12.7
	3/4	19.1
	1	25.4
THICKNESS, T, MIN	1/4	6.4
	3/8	9.5
	1/2	12.7
	5/8	15.9
WIDTH, W	3	76.2
	3	76.2
	3	76.2
	3 1/2	88.9
FILLET LENGTH, C	1 1/2	38.1
	1 1/2	38.1
	1 1/2	38.1
	1	25.4

NOTE: SEE SPECIFICATION FOR ADDITIONAL DETAILS.

FIGURE 22-14 **Longitudinal fillet weld test.**

22-2 VISUAL INSPECTION

Visual examination is a nondestructive testing technique or evaluation method. It is by far the most popular and most widely used. It is extremely effective, and is the least expensive inspection method. The welding inspector can utilize visual inspection throughout the entire production cycle of a weldment. It is an effective quality control method which will ensure procedure conformity and will also catch errors at early stages. The work of the welding inspector utilizing visual inspection methods can be subdivided into three main divisions: (1) visual examination prior to welding, (2) visual examination during welding operations, and (3) visual examination of the finished weldment.

Visual Examination Prior to Welding

As a quality control technique there are a great many items that must be reviewed and checked prior to welding. These include:

1. Review all applicable drawings, specifications, procedures, welder qualifications, etc. This helps the inspector to become familiar with the job and all specifications that apply to it.
2. Review the material specifications of the parts comprising the weldment and determine that the materials are according to specifications.
3. Compare the edge preparation of each joint with the drawings. At the same time, check edge preparation for surface conditions.
4. Check the dimensions of each item since they will effect weldment fitup.
5. At the fitup operation check assembly dimensions and fitup with special emphasis on root openings of the weld joints.
6. At the fitup operation check the backing bars, rings, copper, flux, etc., to be sure that they are in accordance with requirements.
7. At the fitup operation, check the cleanliness of the welding joints and the conditions of tack welds.

At the fitup and tack weld operations, many weldments are completely fitted and ready for production welding. In other cases certain welds may later be hidden and these welds must be completed before fitup is finished. It is recommended good practice for the fitter to mark in chalk the weld symbols showing weld sizes for all welds to be made by the production welders. On high-volume production work this may not be necessary, especially if samples of production parts are available for reference.

At the fitup station, the welding inspector should check the tack welds to determine that the correct electrode types are being used for the base metal that is being welded; also, to see if any special precautions such as preheat are required. If preheating is specified, local preheating may be the answer at this point of production.

Visual Examination during the Welding Operation

Also as a quality control technique when welding begins, there are several items that should be checked including the welding procedures. Make sure that they are in order, applicable to the weldment, and available to the people doing the welding. Items that must be checked are:

1. Determine that the designated welding process and method of application to be employed are in accordance with procedures.

2. Determine that the designated electrodes or filler metal is proper for base metals to be welded and will be employed. Determine the storage facilities, the condition of electrodes, and for critical work, record the heat numbers of the electrodes utilized in specific joints or weldments.
3. Make a survey of the welding equipment to make sure that it is in good operating condition. This should include clamping devices, fixtures, locating devices, etc.
4. Determine that the correct welding current and the proper polarity are being used.
5. Determine that preheat requirements are adhered to at the time of welding. This involves checking temperatures of base metal and determining that base metal temperatures are heat-soaking temperatures instead of merely surface heat. The time of preheating can help establish whether through-heating is accomplished. Preheat temperatures can be checked by the use of temperature-indicating devices.
6. Identify all welders assigned to the particular weldment or job or joint in question. Their qualification level must be in accordance with the requirements of the job. Qualification papers should be reviewed to determine that they are in order and have not expired.
7. Observe welders making welds. This has a rather startling effect on welders, especially when they know that their welds are being watched as they are being made. If a welder does not appear to have the necessary skill for the job in question, the inspector can, in consultation with the supervisor, request that the welder make requalification tests. This requirement is not always in all codes but is common practice for high-quality work.
8. Determine that interpass temperatures are being maintained during the welding operations. If welding operations are discontinued for a period, the interpass temperatures must be obtained before welding is resumed.
9. Determine also that interpass cleaning by chipping, grinding, gouging, etc., is being done in accordance with the requirements of the procedure or specification or in accordance with good practice.

With the welding inspector on the site during welding operations, it is possible for any unusual activities or repair to be noticed. This type of work is often required but should have special attention and supervision to determine that the quality requirements are maintained. In many situations repair work, must be described and approved prior to doing the work.

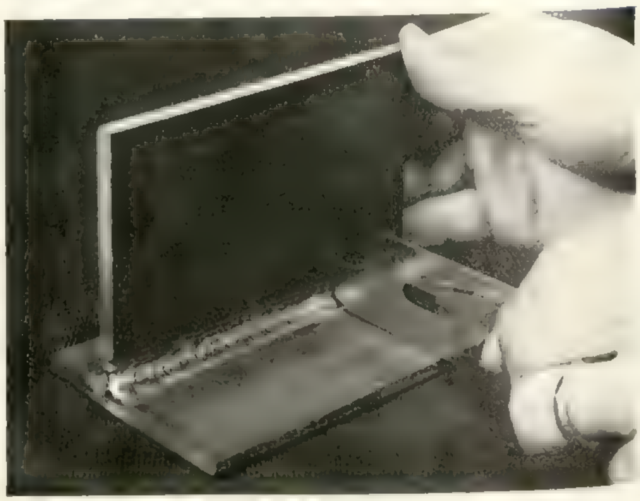
1. The inspector must document all repair welding, why it was required, the extent of the work, and how it was done. This should be recorded in an inspection notebook or on applicable report forms, whichever is required.
2. The inspector should determine that any type of postheat treatment performed is done in accordance with the procedure or other requirements.
3. Finally, the inspector should check any warpage corrective activities such as press work, thermal bending, etc., that might be employed. It is also necessary that these types of activities be recorded in the inspection notebook.

Visual Examination after Welding on the Completed Weldment

The inspector is expected to determine that the weldment conforms to the drawings and specifications for which it is designed and constructed. This includes many items with respect to the weldment but more importantly to the welds. The welds must all be made to the size specified.

1. It is important to check the weld size of all welds. This is not as difficult as it might sound. By means of weld gauges, the size of fillet welds can easily be determined. Figure 22-15 shows the use of a standard fillet weld gauge used in North America. Figure 22-16 shows the size of fillet welds and the method of checking fillet welds to determine that they do meet the size specifications. There are many other types of gauges. Figure 22-17 shows the use of a U.S. Navy gauge for checking fillets. There are other gauges, primarily from Europe, that are used throughout the world, including North America. One of the most popular is the British gauge shown in Figure 22-18. It has many capabilities for checking many sizes of different types of welds.

FIGURE 22-15 Use of standard fillet gauge.



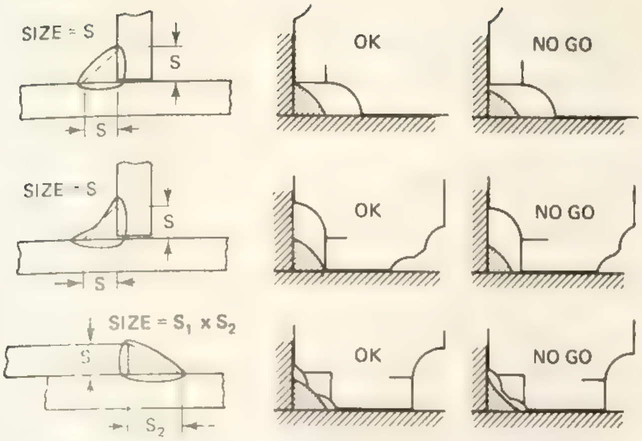
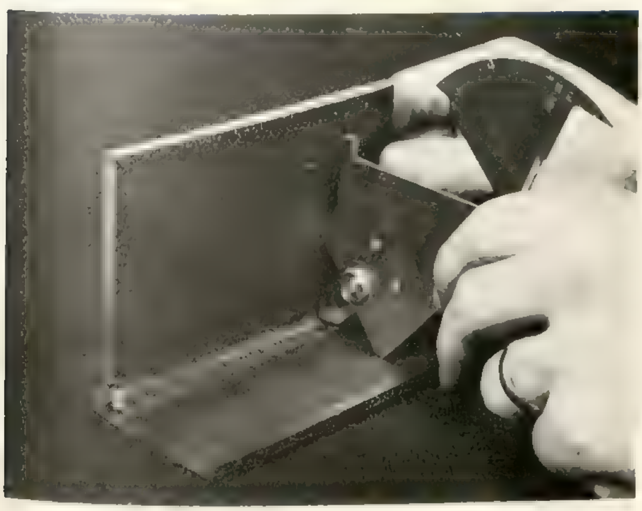


FIGURE 22-16 Fillet weld size and method of checking.

FIGURE 22-17 Navy type weld gauge.

FIGURE 22-18 British welding gauge.



2. All welds should be inspected to see that they do not have any of the defects listed below.

   Surface cracks (including toe cracks)
   Crater cracks (or unfilled crater)
   Surface porosity
   Incomplete root penetration
   Undercut
   Underfill on face, groove, or fillet (concave)
   Underfill of root (suck-back)
   Excessive face reinforcement, groove, or fillet (convex)
   Excessive root reinforcement (or drop-through)
   Overlap
   Misalignment (high–low)
   Arc strikes
   Excessive spatter

   Each of these defects is described in detail in Section 22-4.

3. The weldment must also be checked by the inspector. The following are considered weldment defects.

Warpage Warpage of weldments can be a reason for rejection or repair work. If warpage is beyond the allowable or acceptable limits, corrective action should be initiated. This can include mechanical methods such as the use of clamps, strong backs, presses, and so on, or thermal methods such as the use of torches. Judgment of the inspector is important. If it is felt that damage can be done to the weldment by means of these remedial actions, records of action taken must be made in the inspection notebook.

Base Metal Defects The inspector must also be on the lookout for these, which can appear as lamination in edges of steel plates. They can also be scabs or seams in the base metal. Caution is particularly important when steel plate is stressed in the through or Z direction.

Backing Welds These must be utilized whenever there is a question about the quality of root fusion of groove welds and corner type fillet weld joints.

Nondestructive Examination Recommendations

The welding inspector should determine if nondestructive testing symbols are on weldment drawings. If so, it is important that the appropriate joints be marked for nondestructive testing and the inspector determine that such tests are made. These tests can involve the use of ultrasonic inspection, magnetic particle inspection, radiographic inspection, or dye-penetrant inspection. Dye-penetrant inspection is sometimes used for root-pass inspection, especially on high-quality pipe weldments.

It is the privilege of the welding inspector, utilizing visual inspection, to call for any of the nondestructive techniques if there is reason to be suspicious of a specific

joint, welder, or weldment. Good practice allows such weldments to be taken and subjected to at least one of the NDT methods. It is expected that the inspector will have reason for making such requests. If such weldments, joints, and so on, do not show defects, it is then wise to determine the competence of the inspector. Visual inspection of the surface of welds or of any metal part will not reveal internal flaws or problems. Surface inspection cannot show the lack of fusion at the root of the weld if the root of the weld is inaccessible for visual inspection. Internal porosity cannot be seen from the surface or internal cracks and other internal defects. It is therefore necessary to allow the inspector the privilege of requiring occasional internal examinations in order for the inspector to maintain credibility with welders.

The welding inspector must have certain qualifications. Under certain circumstances on some types of work, it is necessary that the welding inspector be qualified and possibly certified. The American Welding Society tests and qualifies welding inspectors.[2] With or without this requirement it is necessary that the inspector have good eyesight corrected to 20–20 vision. The inspector must also be given the necessary tools and instruments for making inspections. This would include welding gauges, measuring instruments, temperature indicators, welding shields, flashlights, notebooks for recording data, and last but not least, a marking crayon, normally yellow or red, which can be used to mark those welds or weldments that must be repaired or rejected. Finally, it is necessary that the welders cooperate with the inspector, that weld slag be removed for adequate inspection, and that critical welds are never covered over before they can be inspected. This type of cooperation will ensure that quality weldments are produced by the team of welders, supervisor, and inspector involved.

22-3 NONDESTRUCTIVE TESTING

Nondestructive testing (NDT) is also known as Nondestructive examination or evaluation (NDE) and Nondestructive inspection (NDI). In any case, this technique is the application of physical principles for the detection of flaws or discontinuities in materials without impairing their usefulness. There are a number of examination methods or techniques. Of all of these examination techniques, visual inspection is the most important and most widely used. The growth of nondestructive testing has been greatly accelerated by the need for higher quality and better reliability of manufactured products.

In the field of welding there are four nondestructive tests which are most widely used: dye-penetrant testing and flourescent-penetrant testing, magnetic particle testing, ultrasonic testing, and radiographic testing. Each of these techniques has specific advantages and limitations. A comparison of the different techniques compared with visual testing is shown to provide guidance in selection of the different tests. For more information see the AWS booklet, "Guide for the Nondestructive Inspection of welds."[3]

Penetrant Examination

Liquid-penetrant examination (PT) is a highly sensitive, nondestructive method for detecting minute discontinuities (flaws) such as cracks, pores, and porosity, which are *open to the surface* of the material being inspected. This method may be applied to many materials, such as ferrous and nonferrous metals, glass, and plastics. Although there are several types of penetrants and developers, they all employ common fundamental principles, as shown in Figure 22-19.

One of the most important aspects of liquid-penetrant examination is the preparation of the part before the penetrant is applied. The surface must be cleaned with a solvent cleaner to remove any dirt or film. Discontinuities must be free from dirt, rust, grease, or paint, to enable the penetrant to enter the surface opening. The solvent cleaner, used to remove the excess penetrant, is excellent for precleaning of the part surfaces.

A liquid penetrant is applied to the surface of the part to be inspected. The penetrant remains on the surface and seeps into any surface opening. The penetrant is drawn into the surface opening by capillary action. The parts may be in any position when tested. After sufficient penetration time has elapsed, the surface is cleaned and excess penetrant is removed. When the surface is dry a powdered, absorbent material or a powder suspended in a liquid is applied. The result is a blotting action which draws the penetrant from any surface opening. The penetrant is usually a red color; therefore, the indication shows up brilliantly against the white background of the developer. The indication is larger than the actual defect. Thus even small defects may be located.

Equipment Portable inspection kits are available for visible dye penetrant. Some of the kits use pressurized cans so that liquids may be sprayed on the parts to be inspected. The use of pressurized liquids is shown in Figure 22-20.

Stationary equipment usually consists of a tank in which the penetrant is applied either by dipping, pouring, or by brushing. Other tanks provide drain, wash, and developer stations. The size of the tanks and individual stations is governed by the sizes and quantities of the parts to be examined. Specialized, high-volume units are available which provide for parts examination at production rate speeds. This equipment utilizes moving conveyors. The operator places the parts on the conveyor and they proceed unattended throughout the entire processing operation. At the end, an inspector examines the parts and interprets the indications.

Applications In the field of welding, liquid-penetrant

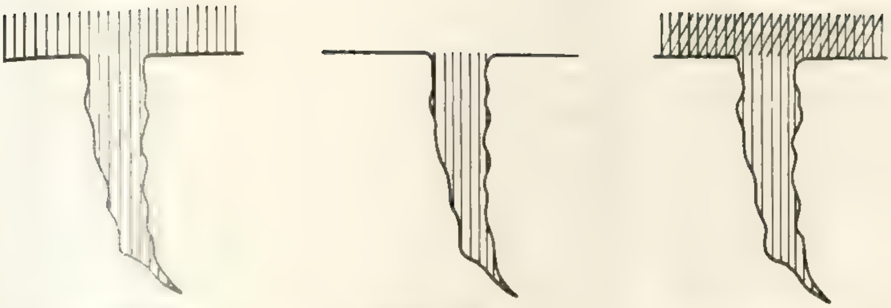


FIGURE 22-19 Principle of penetrant examination.

FIGURE 22-20 Using penetrant on finished weld.

examination is used to detect surface defects in aluminum, magnesium, and stainless steel weldments when the magnetic particle examination method cannot be used. It is very useful for locating leaks in all types of welds. Welds in pressure and storage vessels and in piping for the petroleum industry are examined for surface cracks and for porosity, using this method.

Fluorescent-Penetrant Examination

The fluorescent-penetrant examination (FPT) technique is almost identical with the dye-penetrant technique. There are two basic differences, however. The penetrant is fluorescent and when it is exposed to ultraviolet or black light it shows as a glowing fluorescent type of readout. It provides a greater contrast than the visible dye penetrants. It is considered to have greater sensitivity.

For the use of the flurescent-penetrant system, the other extra piece of equipment required is the ultraviolet or black light source. It is recommended that the inspection be done in a darkened area with the black light as the predominant source of light available.

Kits similar to the dye-penetrant equipment are also available for fluorescent-penetrant examination; however, it is probably more popularly used with liquid penetrants in tanks similar to that mentioned for dye penetrant but with the fluorescent-penetrant material and the black light for examination.

Examination is made using the ultraviolet or the black light. Sound areas appear deep violet while the defects will glow a brilliant yellowish-green. The width and brightness of the fluorescent indication depends on the size of the crack or defect.

Applications Probably one of the most useful applications of fluorescent-penetrant examination is for leak detection in magnetic and nonmagnetic weldments. A florescent penetrant is applied to one side of the joint and a portable ultraviolet light (black light) is then used on the reverse side of the joint to examine the weld for leaks. Flourescent-penetrant examination is also widely used to inspect the root pass of highly critical pipe welds.

Interpretation When visible dye penetrants are used, defects are indicated by the presence of a red color against the white background of the developer. A crack appears as a continuous line indication. The width and brightness of the dye indication depend on the volume of the crack or defect. Figure 22-21 shows a typical indication.

FIGURE 22-21 Penetrant indication.

A *cold shut* (lap) which is caused by imperfect fusion is smooth in outline and continuous. Penetrant indications of gas holes appear round with definite color contrast.

The most effective aid for identifying and recognizing defects is a collection of parts containing defects. These can be compared to parts containing unknown indications. Extreme care and judgment must be exercised in interpreting indications. Consult the specification involved for standards of acceptability and qualification of operators.

Magnetic Particle Examination

Magnetic particle examination (MT) is a nondestructive method of detecting cracks, porosity, seams, inclusions, lack of fusion, and other discontinuities in ferromagnetic materials. Surface discontinuities and shallow subsurface discontinuities can be detected by using this method. There is no restriction as to the size and shape of the parts to be inspected; *only ferromagnetic materials can be examined by this method.*

This examination method consists of establishing a magnetic field in the test object, applying magnetic particles to the surface of the test object, and examining the surface for accumulations of the particles which are the indications of detects.

Ferromagnetism is the property of some metals, mainly iron and steel, to attract other pieces of iron and steel. A magnet will attract magnetic particles to its ends or poles, as they are called. Magnetic lines of force or flux flow between the poles of a magnet. Magnets will attract magnetic materials only where the lines of force enter or leave the magnet at the poles.

If a magnet is bent and the two poles are joined so as to form a closed ring, no external poles exist and hence it will have no attraction for magnetic materials. This is the basic principle of magnetic particle inspection. As long as the part is free of cracks or other discontinuities, magnetic particles will not be attracted. When a crack is present, north and south magnetic poles are set up at the edge of the crack. The magnetic particles will be attracted to the poles which are the edges of the crack or discontinuity (Figure 22-22).

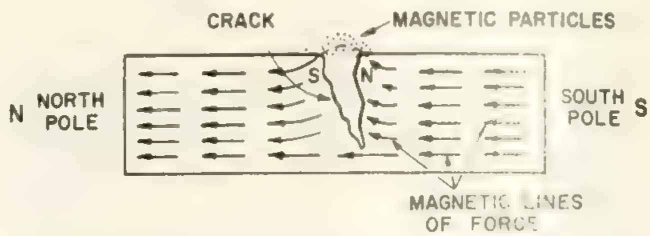


FIGURE 22-22 Principle of magnetic particle examination.

Electric currents are used to induce magnetic fields in ferromagnetic materials. An electric current passing through a straight conductor creates a circular magnetic field. For reliable examination, the magnetic lines of force should be at right angles to the defect to be detected. Hence, for a straight conductor with a circular field, any defect parallel to the conductor will be detected.

If the part is too large to run current through it, the part can be circularly magnetized by using probe contacts (Figure 22-23). Direct current is the most desirable type of current for subsurface discontinuities. It is most

FIGURE 22-23 Using magnetic particle examination.

commonly used for wet magnetic particle inspection. For dry particles, pulsating dc is used for both surface and subsurface defects. This current causes the particles to pulse, which gives them mobility and aids in the formation of indications. Alternating current tends to magnetize the cracks of the metal only, and hence it is used only for surface discontinuities such as fatigue or cracks caused by grinding.

Ferromagnetic parts that have been magnetized retain a certain amount of residual magnetism. Certain parts may require demagnetization if they are to function properly. The attraction of small chips or particles caused by the residual magnetism may cause excessive wear and failures with rotating parts such as bearings and bearing surfaces.

Equipment The most necessary piece of equipment for magnetic particle examination is the *specialized power source*. Small portable units are available which supply ac while operating from 115-V ac power lines. These units generally use dry powder, but portable magnetic particle units which employ a pressurized spray may also be used.

Stationary units are widely used for examination of small manufactured parts. These units usually contain a built-in tank with a pump which agitates the wet particle bath and pumps the fluid through a hose for application to the test parts. These stationary units are usually provided with an inspection hood; ultraviolet or black light can be used so that fluorescent particles can be used and viewed.

Applications The iron particles can be applied as dry powder or suspended in a liquid. Magnetic particle examination may be applied to all types of weldments. On multipass welds, it is sometimes used to examine each pass immediately after it has been deposited. An indication using the dry powder method is shown in Figure 22-24.

The majority of steel weldments in the aircraft industry are examined by the magnetic particle method. If the weldments are thin enough, this method may provide sufficient sensitivity to detect any subsurface defects. Consult the specification involved for standards of acceptability and qualifications of equipment and operators. Parts may have to be demagnetized after testing.

FIGURE 22-24 Magnetic powder indication.

Radiographic Examination

Radiography is a nondestructive examination method which uses invisible, X-ray, or gamma radiation to examine the interior of materials. Radiographic examination (RT) gives a permanent film record of defects which is relatively easy to interpret. Although this is a slow and expensive method of nondestructive examination, it is a positive method for detecting porosity, inclusions, cracks, and voids in the interior of castings, welds, and other structures.

X-rays, generated by electron bombardment of tungsten, and gamma rays emitted by radioactive elements, are penetrating radiation whose intensity is modified by passage through a material. The amount of energy absorbed by a material depends on its thickness and density. Thus a thinner part will absorb less energy than a thick part and a heavy dense metal, such as steel, will absorb more energy than a light metal such as aluminum. Energy not absorbed by the material will cause exposure of the radiographic film. These areas will be dark when the film is developed. Areas of the film exposed to less energy remain lighter. Therefore, areas of the material where the thickness has been changed by discontinuities, such as porosity or cracks, will appear as dark outlines on the film. Inclusions of low density, such as slag, will appear as dark areas on the film while inclusions of high density, such as tungsten, will appear as light areas. All discontinuities are detected by viewing shape and variations in the density of the processed film.

The x-ray or gamma ray source and penetrameter are placed above the piece to be radiographed and the film is placed on the opposite side of the part (Figure 22-25). Figure 22-26 shows an oil-cooled and shielded head, which encloses the x-ray tube, being positioned to make a radiograph of a weld test plate.

Equipment X-rays are produced by electrons hitting a tungsten target inside an x-ray tube. In addition to the x-ray tube, the apparatus consists of a high-voltage generator with necessary controls. X-rays are produced

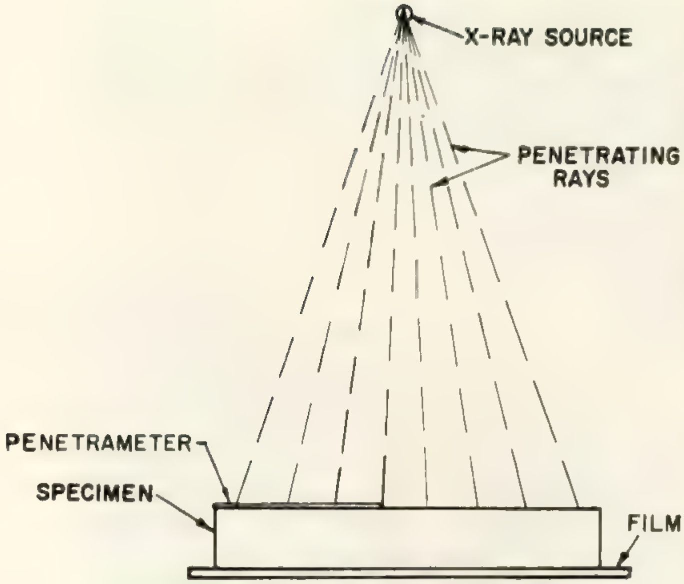


FIGURE 22-25 Principle of radiographic examination.

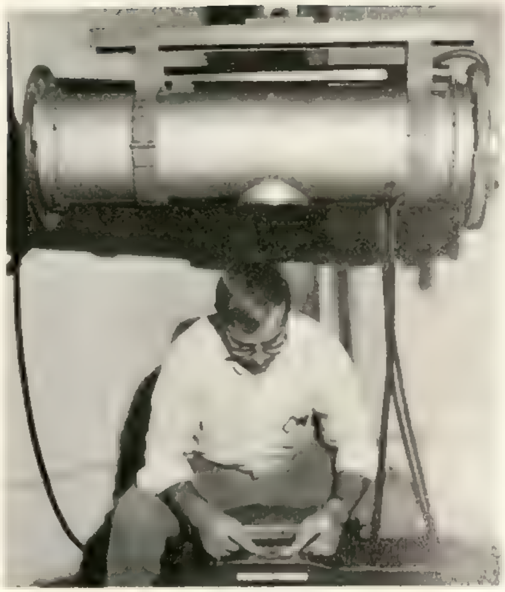


FIGURE 22-26 Setting up to take radiograph.

when a high-speed stream of electrons collides with a piece of tungsten. The electrons are produced in the x-ray tube by a hot cathode. They are accelerated towards the anode by means of an electron gun in the vacuum of the x-ray tube. The anode is a piece of tungsten, and when the electrons hit it x-rays are produced, which are directed through a window to the part being inspected.

Gamma rays are produced by radioactive decay of certain radioisotopes. The radioisotopes normally used are cobalt-60, iridium-192, thulium-170, and cesium-137. These isotopes are contained in a lead or spent uranium vault or capsule to provide safe handling. They have a relatively short half-life and the strength of the radiation decreases with time.

Isotopes must be handled in such a way that radiographic sources can be positioned and yet produce minimum radiation hazards to operating personnel. Remote handling equipment is employed when the radioactive source is drawn from the shielded container to the material to be radiographed. In the United States a license from the U.S. Department of Energy is required for use of radioisotopes.

The radiation intensity or output from an x-ray machine or from radioisotope sources will vary. Common materials such as concrete and steel are used to house the x-ray machine and protect the operator from exposure. The thickness of the shielding enclosure walls should be sufficient to reduce exposure in all occupied areas to a minimum value. If the work is too large or too heavy to be brought into the shielded room, special precautions such as lead-lined booths and portable screens are used to protect personnel. In the field, radiography protection is usually obtained from distance alone, since radiation intensity decreases as distance increases.

Penetrameters are used to determine the sensitivity of the radiograph. They are made of the same material that is being inspected and are usually 2% of the thickness of the part being tested. Therefore, if the penetrameter can be seen clearly on the radiograph, any change in thickness of the part (2% or more) will be seen clearly.

Radiographic film consists of a transparent plastic sheet coated with a photographic emulsion. When x-rays strike the emulsion, an image is produced. The image is made visible and permanent by a film-processing operation. Most processing equipment consists of tanks which contain a developer, a fixer, and rinse solutions. Film-processing operations are just as critical as the film exposure. Unsatisfactory radiographs can sometimes be attributed to errors in the processing technique or from mishandling of materials.

Application Radiography is one of the most popular nondestructive examination methods for locating subsurface defects. It is used for examination of weldments in all types of materials: steel, aluminum, magnesium, and so on. Radiography is used in the pipeline industry to ensure proper weld quality.

Interpretations Most indications will show up as dark regions against the light background of the sound weld. Radiographs should be examined with a film illuminator providing a strong light source. Figure 22-27 shows a radiograph being examined.

It is essential that qualified personnel conduct X-ray interpretations since false interpretation of radiographs causes a loss of time and money. Radiographs for reference are extremely helpful in securing correct interpretations. Consult the specification involved for stan-

FIGURE 22-27 Examination of a radiograph.

dards of acceptability and qualifications of equipment and operators. See IIW reference radiographs,[4] Hobart pipeline radio graphs and interpretations.[5]

Ultrasonic Examination

Ultrasonic examination (UT) is a nondestructive examination method which employs mechanical vibrations similar to sound waves but of a higher frequency. A beam of ultrasonic energy is directed into the specimen to be examined. This beam travels through a material with only a small loss, except when it is intercepted and reflected by a discontinuity or by a change in material.

Ultrasonic examination is capable of finding *surface and subsurface* discontinuities. The ultrasonic contact pulse reflection technique is used. This system uses a transducer, which changes electrical energy into mechanical energy. The transducer is excited by a high-frequency voltage which causes a crystal to vibrate mechanically. The crystal probe becomes the source of ultrasonic mechanical vibrations. These vibrations are transmitted into the test piece through a coupling fluid, usually a film of oil, called a *couplant*. When the pulse of ultrasonic waves strikes a discontinuity in the test piece, it is reflected back to its point of origin. Thus the energy returns to the transducer. The transducer now serves as a receiver for the reflected energy. The initial signal or main bang, the returned echoes from the discontinuities, and the echo of the rear surface of the test material are all displayed by a trace on the screen of a cathode-ray oscilloscope. Videotapes may be used for permanent records.

The basic principles of ultrasonic examination are shown in Figure 22-28. The transducer is sending out a beam of ultrasonic energy. Some of the energy is reflected by the internal flaw and the remainder is reflected by the back surface of the specimen. Figure 22-29 shows the equipment in use.

Figure 22-30 shows a typical display as presented on the oscilloscope screen. Signal strength is indicated by a vertical deflection of the pip on the screen and transmitted time is indicated by horizontal deflection. By measuring the height of the pip, the size of the flaw can be determined. The depth of the flaw from the surface is found by use of horizontal base. The front reflection

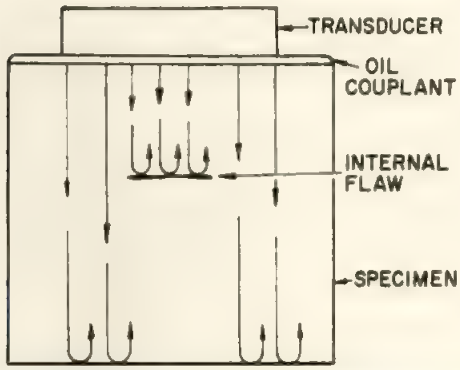
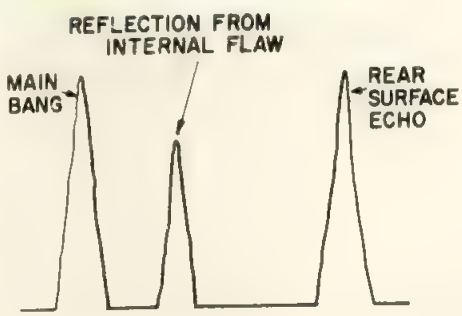


FIGURE 22-28 Principle of ultrasonic examination.

FIGURE 22-29 Making an ultrasonic examination of a weld.

FIGURE 22-30 Oscillograph display.



and the rear reflection are at the extreme ends of the screen. The echo from the flaw is between the two.

To determine the size and depth of flaws, calibration techniques and reference standards must be used. A set of test blanks which have holes of known diameter and depth is used to calibrate the test instrument. The reference standard is described in detail by the AWS structural code.

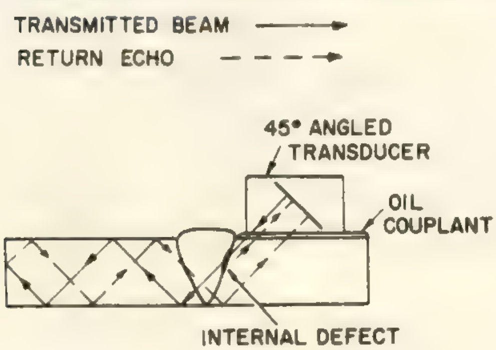
Testing can be done with one transducer which serves both as a transmitter and receiver, or with two transducers, one transmitting only, and the other receiving only. The single transducer is used for portable equipment.

For examining irregularly shaped parts, the immersion testing method is often used. With this method, the part and the transducer are submerged in water. The water transmits and couples the ultrasonic beam and the part. Actual contact is not required, thus irregular surfaces can be scanned.

The application of ultrasonic examination to weldments is shown in Figure 22-31. A 45° angled beam transducer is used to inspect the weld area. This search unit directs the beam toward the weld from a position on one side of the weld.

Butt joint welds in plate are usually examined with the angled search unit. The reflection obtained by the use of the 45° head is similar to Figure 22-30. The joint welds of heavy plate are examined with a straight beam transducer through the top of the joint, or with an angled beam transducer from one side of the bottom. Fillet welds are more difficult to examine.

FIGURE 22-31 45° use of ultrasonic inspection.



Equipment Equipment required for this process consists of a transducer, pulse rate generator, amplifier, timer and cathode ray oscilloscope. These devices are electronic, quite small in size for portability, yet rugged. Instant cameras are available to photograph oscilloscope displays for permanent records. Tapes can also be used.

Application Ultrasonic examination can be used to test practically any metal or material. Its use is restricted only by very complex weldments. The process is increasing in popularity and widely used. Consult the specification involved for standards of acceptability and qualification of equipment and operators.

Leak Testing

Leak testing (LT) can be accomplished in many different ways. It can be used only when the weldment can be made to contain a gas or liquid. The most common leak test is the soap bubble test, which can be applied to external joints if internal gas pressure is present. Another is the use of internal liquids and the maintaining of high pressure over an extended period. The same test can utilize a vacuum. Halogen gases with sensitive detection meters are used to inspect production parts.

Do not use toxic or flammable gases or air for internal pressure testing. The internal pressure will store energy and if the part should fail it could cause an explosion that might cause bodily harm. Use internal liquids instead, or test inside a safety chamber.

Proof Testing

Proof testing (PRT) is controversial. In the past proof testing was used on vessels and mechanical components. It consisted of loading the part 50 or 100% greater than the designed load. It was felt that if the part passed this test and if it was never loaded above its designed load that it would never fail in service. It is now thought that proof testing could cause internal damage that might reduce service life. Also, proof testing cannot provide assurance if the part is subjected to corrosion, fatigue, low-temperature impacts, and so on. Consider proof testing but only in light of the above. Its use is declining.

Guide to NDT Techniques

Figure 22-32 is a guide to welding quality control comparing the different nondestructive examination techniques. This table shows the equipment required, the defects that can be detected, the advantages and disadvantages of each technique, and other factors.

22-4 CORRECTIVE ACTIONS FOR WELD DEFECTS

The problem of weld defects has become quite complex in the last few years, partially because of the great number of different words and definitions that are being used. For example, a welding flaw is a synonym for discontinuity; *discontinuity* is the preferred term. A discontinuity is "an interruption of the typical structure of a material such as a lack of homogeneity in its mechanical, metallurgical or physical characteristics. A discontinuity is not necessarily a defect. A defect is "a discontinuity or discontinuities that by nature or ac-

FIGURE 22-32 **Guide to weld quality control techniques.**

Examination Technique	Equipment	Defects Detected	Advantages	Disadvantages	Other Considerations
Visual VT	Pocket magnifier, welding viewer, flashlight, weld gauge, scale, etc.	Weld preparation, fitup, cleanliness, roughness, spatter, undercuts, overlaps, weld contour and size; welding procedures	Easy to use; fast, inexpensive, usable at all stages of production	For surface conditions only; dependent on subjective opinion of inspector	Most universally used examination method
Dye penetrant or fluorescent DPT, FPT	Fluorescent or visible penetrating liquids and developers; ultraviolet light for the fluorescent type	Defects open to the surface only; good for leak detection	Detects very small, tight, surface imperfections, easy to apply and to interpret; inexpensive; use on magnetic or nonmagnetic materials	Time consuming in the various steps of the process; normally, no permanent record	Often used on root pass of highly critical pipe welds; if material improperly cleaned, some indications may be misleading
Magnetic particle MT	Iron particles, wet or dry, or fluorescent; special power source; ultraviolet light for the fluorescent type	Surface and near-surface discontinuities, cracks, etc.; porosity, slag, etc.	Indicates discontinuities not visible to the naked eye; useful in checking edges prior to welding, also, repairs; no size restriction	Used on magnetic materials only; surface roughness may distort magnetic field; normally, no permanent record	Examination should be from two perpendicular directions to catch discontinuities which may be parallel to one set of magnetic lines of force
Radiographic RT	X-ray or gamma ray; source: film processing equipment, film viewing equipment, penetrameters	Most internal discontinuities and flaws; limited by direction of discontinuity	Provides permanent record; indicates both surface and internal flaws; applicable on all materials	Usually not suitable for fillet weld inspection; film exposure and processing critical; slow and expensive	Most popular technique for subsurface inspection; required by some codes and specifications
Ultrasonic UT	Ultrasonic units and probes; reference and comparison patterns	Can locate all internal flaws located by other methods with the addition of exceptionally small flaws	Extremely sensitive; use restricted only by very complex weldments; can be used on all materials	Demands highly developed interpretation skill	Required by some codes and specifications

cumulated effect render a part or product unable to meet minimum applicable acceptance standards or specifications." This term designates rejectability. A defective weld then becomes "a weld containing one or more defects." For our purposes, we will consider defects as anything undesirable in a weld. It may or may not be cause for rejection or cause for repair. This is normally a matter left up to the specifications or codes involved. It is important that we learn to recognize the different types of weld defects and learn enough about them so that we can recognize them, repair them, and avoid them.

Shown below is a collection of photographs and drawings of the possible different welding defects that can occur. It is an effort to present, in an organized manner, the various defects that can occur, the description of the particular defect or problem, and an indication of how or what caused the problem and the action that should be taken to correct the specific problem. The presentation may not describe all possible weld defects. There are others and some of the defects described may occur on different types of welds, but they would generally resemble those presented.

In this collection, an effort is made to indicate the responsibility for each of the defects. This breakdown is broad, but will indicate whether it is the fault of the welder, that is, a problem of welding technique, the fault of the designer, that is, a drawing or design error, or a fault of some manufacturing or shop function, such as materials preparation. In the figures these are designated as a *welder* responsibility, *designer* responsibility, or a *shop* responsibility.

An indication of how the particular defect was detected will also be given. This is based on the inspection techniques used to find the defect. The five most popular nondestructive examination techniques are as follows:

- VT Visual examination
- MT Magnetic particle examination
- PT Dye-penetrant examination (including flourescent)
- RT Radiographic examination
- UT Ultrasonic examination

The corrective action for the particular defect is briefly mentioned. Corrective action means the way to correct the specific defect in order to make the weldment suitable for service. Efforts will also be made to provide an explanation to prevent a recurrence of the same type of defect. This may be covered in the general information concerning the different classifications of defects.

The defects are arranged according to the classification of weld defect system established by Commission V of the International Institute of Welding. Their document IIS/IIW-340-69 and Commission V Document[6] classifies the defects into six groups:

- *Series 100, Cracks:* including longitudinal, transverse, radiation, crater, etc.
- *Series 200, Cavities:* including gas pockets, internal porosity, surface porosity, shrinkage, etc.
- *Series 300, Solid inclusions:* including slag, flux, metal oxides, foreign material, etc.
- *Series 400, Incomplete fusion or penetration:* including incomplete fusion, incomplete penetration, etc.
- *Series 500, Imperfect shape or unacceptable contour:* Including undercut, excessive reinforcement, underfill, fillet shape, overlap, etc.
- *Series 600, Miscellaneous defects not included above:* including arc strikes, excessive spatter, rough surface, etc.

This International Institute of Welding document catalogs all welding defects and provides index numbers of three digits for groups and four digits for specific types of defects within the groups. It also cross indexes with the International Institute of Welding Radiographic Reference Radiographics.

The examples of defects presented here are shown to illustrate the problems, and no reference is made to what is acceptable or allowable. To determine the acceptability limits of these different defects you must refer to the specification or code that is involved. Certain defects of a minor nature may be acceptable under specific conditions in some codes, whereas they may be unacceptable in other codes. In general, defects that can propagate under stress are not acceptable in any code; for example, cracks are not allowed in any of the major codes but porosity of a specific magnitude and spacing may be acceptable. Detailed information is found in the book, "Welding Inspection."[7]

There are other problem areas encountered in welding that are not specifically included. These would include such factors as distortion and warping, brittle heat-affected zones, brittle weld metal, arc blow, and so on. These topics are covered elsewhere in the book.

Series 100

Cracks are the first category of weld defects. A crack is "a fracture-type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement." Cracks are perhaps the most serious of the defects that occur in the welds or weld joints in weldments. However, cracks are defects that can be found in other metal products such as forgings, castings, and even hot rolled steel products. Cracks are considered dangerous because they create a serious reduction in strength. They can propagate and cause sudden failure. They are most serious when impact loading and cold-temperature service are involved. Cracks must be repaired.

There are many different types of cracks. One way

of categorizing them is as surface or subsurface cracks. *Surface cracks* can be seen on the surface of the weld using the visual testing technique. There are several types of surface cracks—transverse, longitudinal, and crater cracks (Figure 22-33). There are also toe cracks in adjacent parent metal which normally come to the surface. The subsurface or internal cracks are also of many types. Some may be in the weld, some in the heat-affected zone—sometimes called *underbead cracks,* (Figure 22-34), at the interface between weld metal and base metal and some completely in the base metal, sometimes called *lamanar tearing.* There can also be microsize cracks as well as macrosize cracks. Sometimes the smaller cracks are called *fissures,* or if the cracks are extremely small they are called *microfissures,* which require special techniques to find.

There is another way of classifying cracks and this is with respect to temperature. There are hot cracks which occur during or immediately after the weld is made or during the cooling cycle. Cold cracks are cracks which occur sometime after the weld is finished, after it has cooled to room temperature. Cold cracks may be delayed hours or even days after the weld is finished. There are also fatigue type cracks which may occur months or years after fabrication as a result of an initiating point and fatigue loading. There are also stress corrosion cracks which are caused by a corrosive atmosphere and a high stress condition.

In general, cracks in welds or cracks adjacent to welds indicate that the weld metal or the base metal has low ductility and that there is high restraint. Any factor that contributes to low ductility of the weld and adjacent metal and high restraint will contribute to cracking. Some of these factors are rapid cooling, high-alloy composition, insufficient heat input, poor joint preparation, incorrect electrode type, and so on. The examples that are shown in Figure 22-35 will help further explain the different types of weld cracks, the probable cause, and corrective action.

FIGURE 22-33 Types of surface cracks of welds.

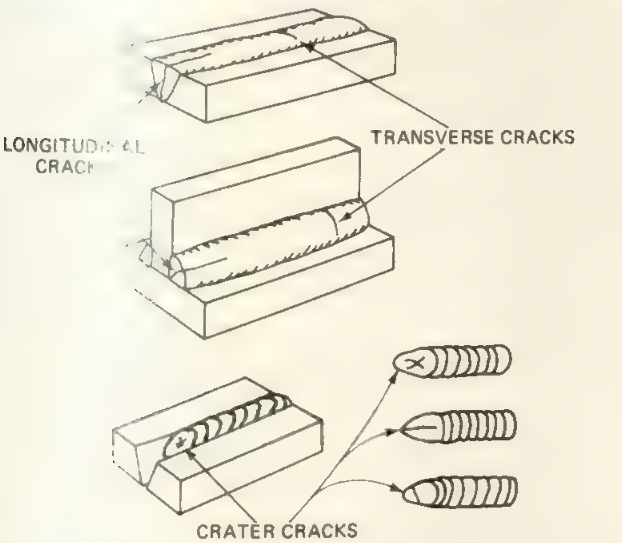
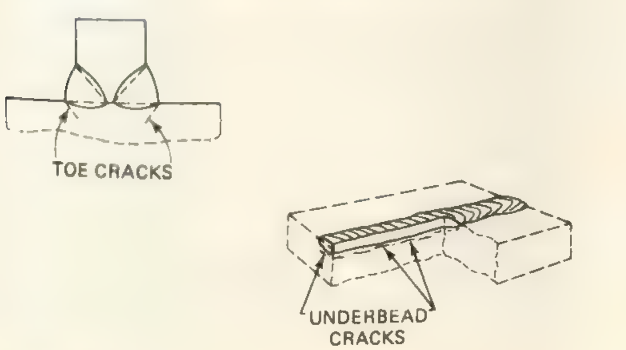


FIGURE 22-34 Weld toe cracks and underbead cracks.



Series 200

Cavities are the second category of defects listed in the IIW document. The most common type of cavity is called porosity, defined as "cavity type discontinuities formed by gas entrapment during solidification." Specific defects can be called *gas pockets* which are cavities caused by entrapped gas. These are sometimes called *blow holes.* Porosity can also be divided into two types: surface porosity, which can be seen by the naked eye and detected by visual inspection technique; and subsurface porosity, which can be found only by the internal detecting techniques. The gas pockets can occur as extremely large holes in the weld metal or extremely small holes scattered throughout the cross section of a weld. Some types of porosity are called *worm holes* when they are long and continuous. Others are called piping, usually long in length and parallel to the root of the weld. Some types may occur exclusively at the root and others almost at the surface. Porosity is not as serious a defect as cracks primarily because porosity cavities usually have rounded ends, and will not propagate like cracks. Many codes and specifications provide comparison charts showing the amount of porosity that may be acceptable. Figure 22-36 shows an example of comparison charts used by the API 1104 code. The AWS structural welding code has taken a slightly different point of view and has a sliding scale (Figure 22-37). This takes into account size and spacing of the porosity and relates to the size of the weld. For more information refer to these codes.

There are other types of cavities and some are called shrinkage voids, which are defined as "a cavity discontinuity normally formed by shrinkage during solidification." Cavities, voids, and porosity are caused by gases that are present in the arc area, or may be present in base metal, that are trapped in the molten weld during the solidification process. Common causes for porosity are

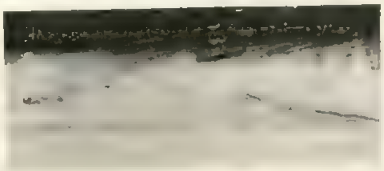
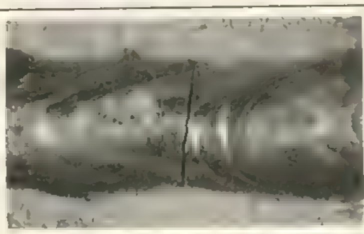
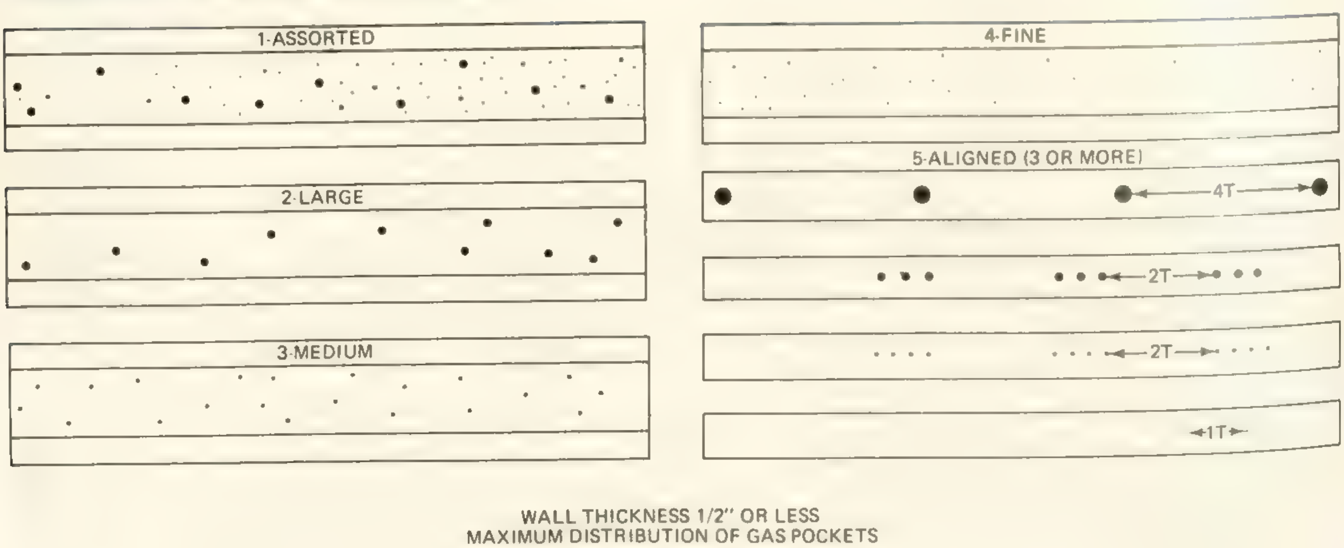
Weld Defect Class — Cracks Appearance or Cross Section or Radiograph Class No. 100		How Defected		Respon-sibility	Probable Cause	Corrective Action
 A	Longitudinal Crack	VT MT PT RT UT	X X X X X	design X welder X shop	General 1. Incorrect electrode. 2. High restraint of joint. 3. Rapid cooling of weld.	1. Use proper or matched electrode. 2. Reduce rigidity of weld ment or change welding sequence. Use higher ductility welding filler metal. 3. Use preheat and/or inner pass heat to reduce cooling rate
 B	Longitudinal Crack	VT MT PT RT UT	 X X X	design X welder X shop	4. Improper joint preparation. 5. Fillet weld longitudinal crack.	4. Use proper joint for welding process 5. Change center line of weld to avoid interface between parts
 C	Crater Crack	VT MT PT RT UT	X X X X X	design welder X shop	Crater Crack 1. Unfilled crater. 2. Crater crack in submerged arc welding.	1. Filler crater with proper techniq 2. Utilize run-out-tal
 D	Transverse Crack	VT MT PT RT UT	X X X X X	design welder X shop X	Transverse Crack 1. Incorrect electrode. 2. Rapid cooling. 3. Welds too small for size of parts joined.	1. Use proper el 2. Use larger ele higher weldin or preheat 3. Use larger weld ly larger welding de.

FIGURE 22-35 Collection of weld defects: cracks.

FIGURE 22-36 Porosity chart for pipe welds.



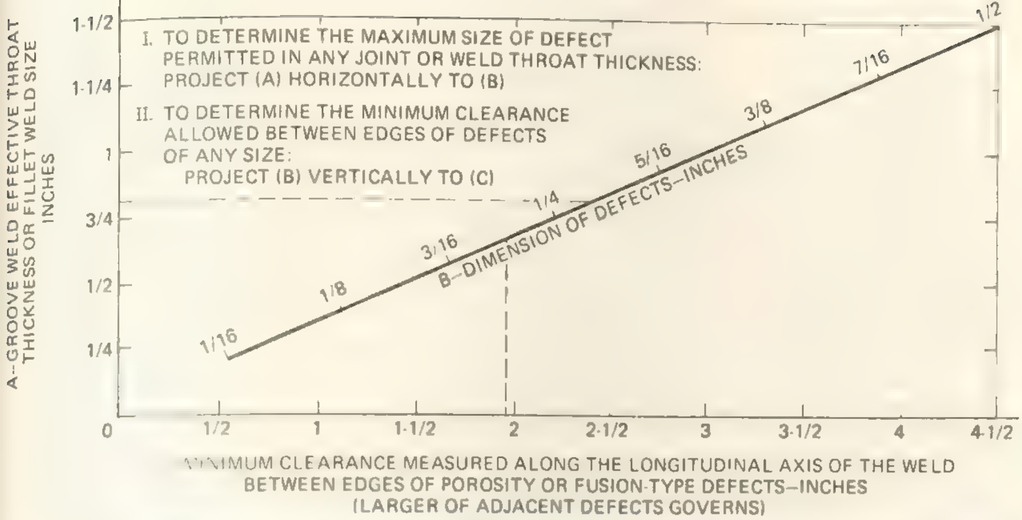
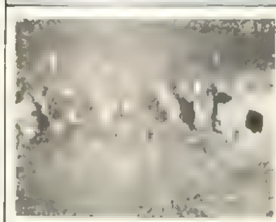
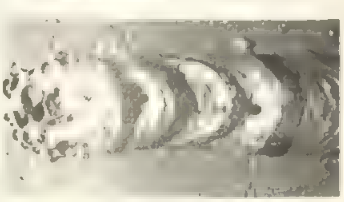
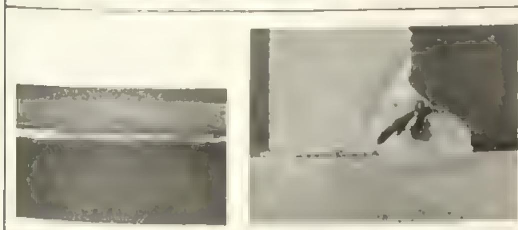


FIGURE 22-37 AWS structural code weld quality requirements.

high sulfur in the base metal, hydrocarbons on the surface of the metal such as paint, water, oil, moisture from damp electrodes, wet submerged arc flux, or wet shielding gas. When the porosity exceeds that acceptable by the code it must be removed and repair welds made. In general, surface porosity is an indication that subsurface porosity may have been in the weld before it became noticeable as surface porosity. In these cases extra inspection should be done to determine the extent of the subsurface porosity. The following examples of cavities will help further explain this type of weld defect. These are shown in Figure 22-38.

FIGURE 22-38 Collection of weld defects: cavities.

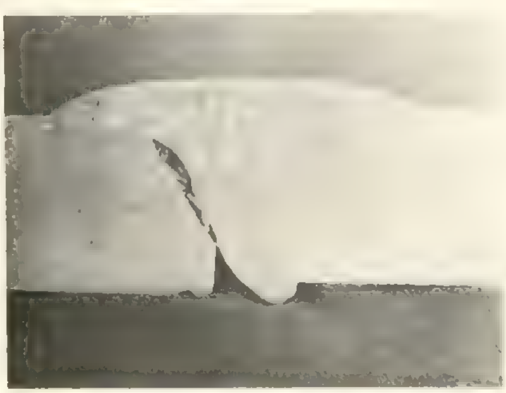
Weld Defect Class – Cavities Appearance or Cross Section or Radiograph Class No. 200	How Detected		Responsibility	Probable Cause	Corrective Action
 A	VT	X	design	**Surface Porosity** General 1. Welding over foreign material on surface such as rust, oil, moisture, paint, etc. 2. Damp electrodes. 3. Improper base metals such as free machining or high sulphur. 4. Welding current too low.	1. Clean weld bevels and area adjacent to weld and keep clean. 2. Use fresh dry electrodes or rebake electrodes that have been exposed to dampness. 3. Utilize correct base metal possibility to use low hydrogen type electrodes. 4. Increase welding current.
	MT		welder		
	PT		X		
	RT		shop		
	UT		X		
 B	VT	X	design	Gas Shielded Welding Processes 1. Incorrect shielding gas type. 2. Incomplete gas coverage due to breeze, defective gas system, clogged nozzle, etc.	1. Use specified shielding gas. 2. Provide windshields, check efficiency of gas system such as broken hoses, gas valves, empty tanks, clean nozzle.
	MT		welder		
	PT		X		
	RT		shop		
	UT		X		
 C	VT	X	design	3. Moisture in the shielding system. 4. Poor gas coverage. 5. Welding over tack weld made with shielded metal arc process.	3. Check to make sure gas is dry or welding grade. Check for water leaks in water cooled systems. 4. Use proper nozzle to work distance. Check gas flow rate, may be too high or too low. 5. Utilize gas metal arc for tack welding.
	MT	X	welder		
	PT	X	X		
	RT	X	shop		
	UT	X	X		
 D	VT	X	design	Submerged Arc Welding 1. Damp submerged arc flux. 2. Contaminated surface of electrode wire, dirt and/or moisture. 3. Too many fines in flux.	1. Utilize fresh dry flux or dry damp flux. 2. Clean surface of electrode wire. 3. Use fresh flux and discard fines.
	MT		welder		
	PT		X		
	RT	X	shop		
	UT	X	X		

Series 300

Solid inclusions are the next type of defect considered by the IIW document. Solid inclusions are normally expected to be a subsurface type of defect and would include any foreign material entrapped in the deposited weld metal. The most common type of solid inclusion is a slag inclusion defined as "nonmetallic solid material entrapped in weld metal or between weld metal and base metal." Another and very similar type of inclusion is a flux inclusion, which is an entrapment of flux from an electrode, from submerged arc flux, or from another source of flux that for one reason or another did not float out of the weld metal as it solidified. Slag inclusions and flux inclusions can be continuous, intermittent, or very randomly spaced. In general, flux or slag inclusions are rounded and do not possess sharp corners like cracks and for this reason are not quite as serious as cracks. The applicable code or specification indicates how much entrapped slag or flux is acceptable.

On certain metals, particularly those that have high-temperature oxide coatings, there is the possibility of oxide inclusions in the weld metal. This is a troublesome problem when welding aluminum. Aluminum oxide will form rapidly in the atmosphere and can be entrapped in the weld metal very easily if cleaning and other precautions are not taken. Oxide inclusions are detected by the internal inspection techniques. There are also other metallic inclusions such as tungsten inclusions which can only be found by internal inspection techniques, particularly radiographic testing. Oxide inclusions or tungsten inclusions are not acceptable for high-quality work. When copper backing bars are used local melting may occur and copper can be entrapped in the weld metal. This can be detected from the underside surface of a weld or by internal detection techniques. All such inclusions are defects that must be evaluated in accordance with the code or specification in question or with respect to good practice. The examples shown in Figure 22-39 will help further explain these types of defects.

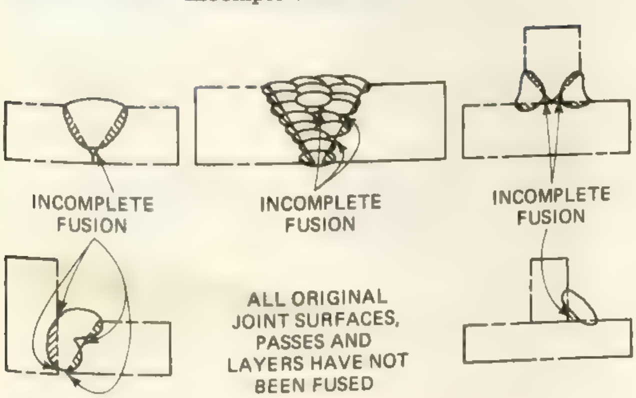
FIGURE 22-39 Collection of weld defects: solid inclusions.

Weld Defect Class — Solid Inclusions Appearance or Cross Section or Radiograph Class No. 300	How Detected		Respon-sibility	Probable Cause	Corrective Action
 A	VT		design	General 1. Slag inclusion-between passes. 2. Intermittent slag inclusion at edge of bead (wagon tracks). 3. Irregular surface of bevels. 4. Incorrect welding technique or wrong current or voltage. 5. Submerged arc welding —flux inclusion.	1. Remove solidified slag after each pass. 2. Remove slag at bead edge. Utilize proper technique to avoid high crowned bead contour 3. Provide for smooth bevel surface, grind if necessary. 4. Utilize correct welding technique for electrode type and joint design 5. Improper direction of electrode wire. Welding current too low. Elect rode wire misdirected possible correction use wire straightener. Improper joint detail.
	MT				
	PT		welder X		
	RT	X	shop		
	UT	X			
 B	VT		design		
	MT				
	PT		welder X		
	RT	X	shop		
	UT	X			
 C	VT		design		
	MT				
	PT		welder X		
	RT	X	shop		
	UT	X	X		

Series 400

Incomplete fusion or *penetration* is the next defect category of the IIW document. This is sometimes called lack of fusion or lack of penetration; however, the preferred term is *incomplete fusion,* defined as "a weld discontinuity in which fusion did not occur between weld metal and fusion faces on adjoining weld beads." It is shown in Figure 22-40. This can be inadequate joint penetration, defined as "joint penetration which is less than specified." The word *penetration* is not preferred; the term should be *joint penetration,* defined as "the distance the weld metal extends from its face into a joint, exclusive of weld reinforcement," or root penetration. *Root penetration* is defined as "the distance the weld metal extends into the joint root" and is shown in Figure 22-41. These illustrations help show the difference between complete and incomplete fusion and complete joint versus partial joint penetration and root penetration. Incomplete fusion as a defect means that the weld deposited did not completely fill the joint preparation or there is space in between the beads or passes or a space at the root of the joint. "Penetration" is a slightly different term. The term "joint penetration" is the minimum depth of the joint; the groove or flange weld extends from its face into the root, exclusive of reinforcement. The term "penetration" means the depth that the groove weld extends into the root of a joint measured on the centerline of the cross section. These terms are often used interchangeably but do have a different meaning. The defect is the absence of complete fusion of a joint and this provides a stress riser, which is undesirable for welds loaded in fatigue or subject to impacts or low-temperature service. Figure 22-42 helps illustrate different types of this defect. The cause of such defects can be dirty surfaces such as heavy mill scale, heavy rust, or grease; failure to remove slag from previous beads; the fact that the root opening may not be sufficiently large; or unsatisfactory welding technique. The danger of the defect is the serious reduction in static strength and the production of a stress riser, as mentioned above.

FIGURE 22-40 Incomplete fusion.



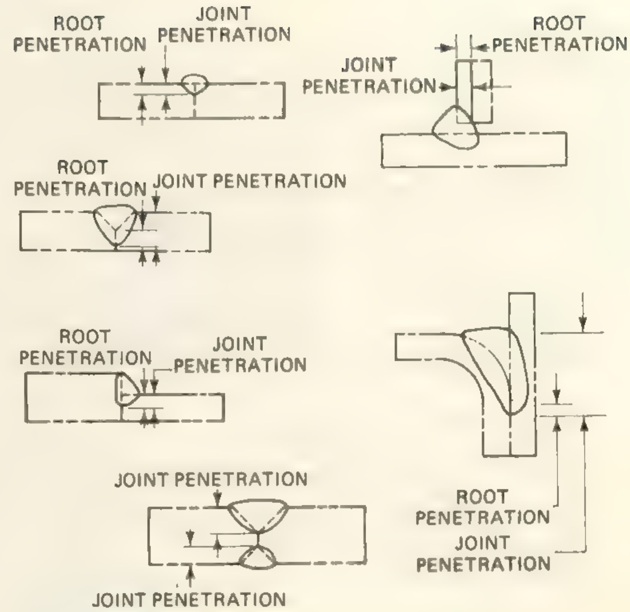


FIGURE 22-41 Root penetration and joint penetration.

Series 500

Imperfect shape, or *unacceptable contour,* is the next category of defect from the IIW document. One of the most serious of these defects is undercut (Figure 22-43). Undercut occurs not only on fillet welds but on groove welds as well. Undercut also produces stress risers that create problems under impact, fatigue, or low-temperature service. It is normally caused by excessive currents, incorrect manipulation of electrode, incorrect electrode angle or type of electrode. Undercut actually refers more to the base metal adjacent to the weld, whereas imperfect shape is a defect of the weld itself. This can include such things as excessive reinforcement on the face of a weld, which can occur on groove welds as well as fillet welds. There is also the problem of excessive reinforcement on the root of the weld, primarily open root groove welds. Excessive reinforcement is an economic waste. It can also be a stress riser and is objectionable from an appearance point of view. It is normally a factor involved with fitup, welder technique, welding current, type of electrode, and so on. A similar flaw is the concave type contour or lack of fill on the face of the weld or a suckback on the root of a groove weld. The proper term in both cases is *underfill,* defined "as a depression on the weld face or root surface extending below the adjacent surface of the base metal" (Figure 22-44). Underfill does reduce the cross-sectional area of the weld below the designed amount and therefore is a point of weakness and potentially a stress riser where failure may initiate. The fillet weld is particularly vulnerable to the problem of imperfect shape. Figure 22-45 shows some dif-

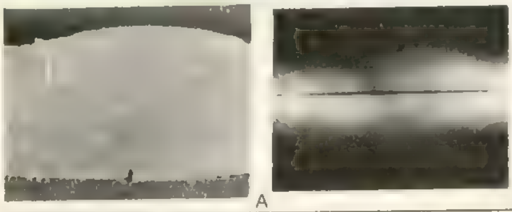
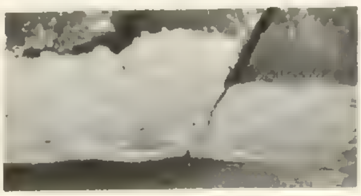
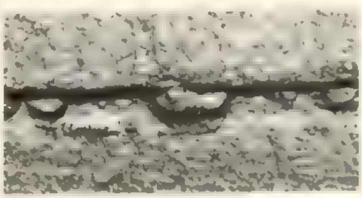
Weld Defect Class — Incomplete Fusion Appearance or Cross Section or Radiograph Class No. 400	How Detected	Respon-sibility	Probable Cause	Corrective Action
 A	VT X MT PT X RT X UT X	design X welder X shop	General 1. Welding speed too fast. 2. Electrode too large for joint detail. 3. Welding current too low. 4. Improper joint design such as excessive root face or minimum root opening..	1. Reduce welding speed. 2. Utilize correct size electrode. 3. Increase welding current for more penetration. 4. Utilize correct joint detail.
 B	VT X MT X PT RT X UT X	design X welder X shop	5. Improper joint fit-up such as root opening too small. Shielded Metal Arc Welding 1. Irregular travel speed. 2. Irregular arc length	5. Make setup correct to agree with joint design detail. 1. High speed will reduce complete fusion, lower speed will cause com plete fusion. 2. Maintain proper arc length.
 C	VT X MT X PT RT X UT	design X welder X shop X	Gas Metal Arc Welding 1. Incomplete fusion—(cold shut)	1. Direct arc at leading edge of puddle. Current too low, voltage too low, adjust for proper pro cedure. Pause too short at dwell when weaving Increase pause to allow melting of base metal.
 D	VT X MT PT RT X UT X	design welder X shop	Submerged Arc Welding—Semiautomatic 1. Incomplete root fusion.	1. Failure to direct welding electrode to root of weld joint.

FIGURE 22-42 Collection of weld defects: incomplete fusion.

FIGURE 22-43 Undercut fillet and groove and overlap.

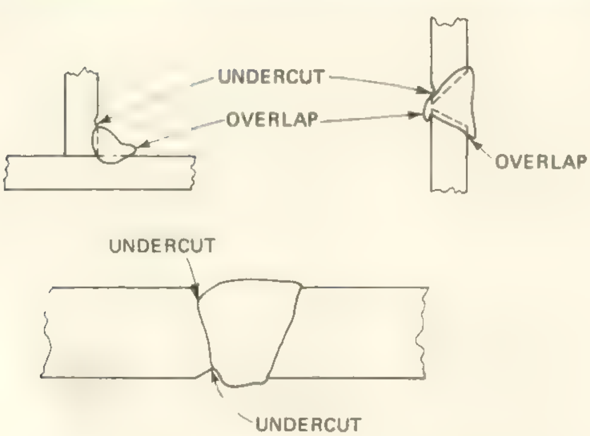
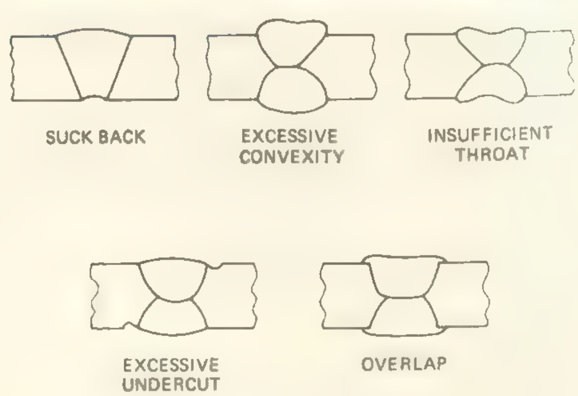


FIGURE 22-44 Groove welds and various defects.



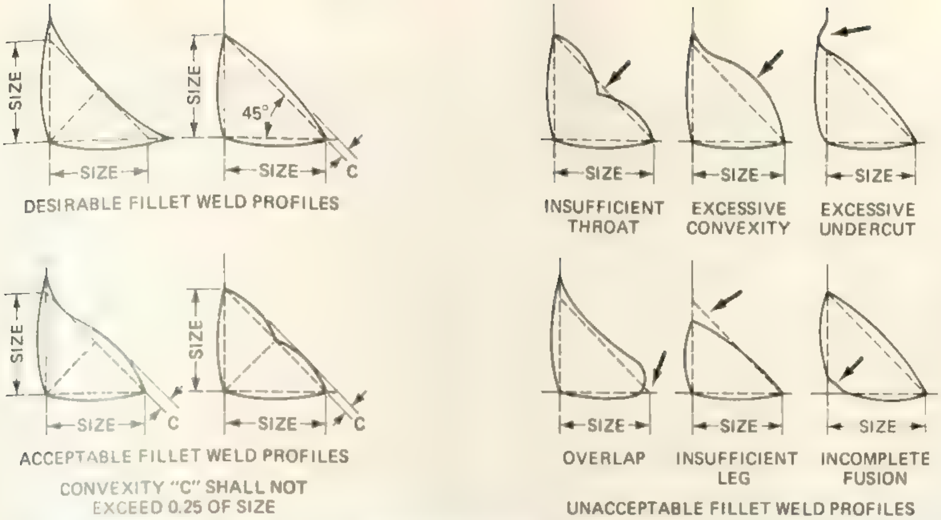


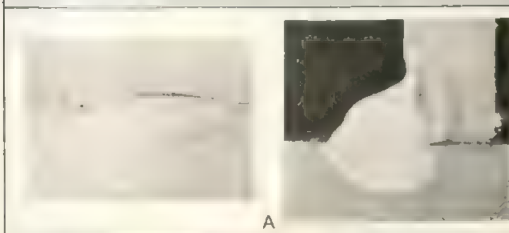
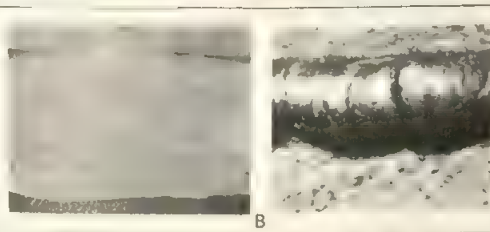
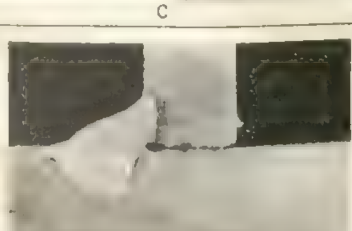
FIGURE 22-45 Contour of fillet welds.

ferent fillet weld contours, both acceptable and unacceptable. Those that reduce the throat of the fillet weld actually reduce the strength of the weld so that premature failure may occur. Examples shown in Figure 22-46 help show the different types of possible defects in this series.

Series 600

Miscellaneous defects are the final category considered and actually cover all defects which may not be categorized in any of the other classifications given above. One

FIGURE 22-46 Collection of weld defects: incorrect shape.

Weld Defect Class — Imperfect Shape Appearance or Cross Section or Radiograph Class No. 500	How Detected		Responsibility	Probable Cause	Corrective Action
 A	VT MT PT RT UT	X X X X X	design welder X shop	Undercutting 1. Faulty electrode manipulation. 2. Welding current too high. 3. Incorrect electrode size (usually too large). 4. Incorrect electrode for welding position. 5. Incorrect electrode angle.	1. Use uniform weave in groove welding pause at edges. 2. Use prescribed welding current for electrode size. 3. Use correct electrode size for size weld being made. 4. Use correct electrode with position capabilities. 5. Adjust electrode angle to fill undercut area.
 B	VT MT PT RT UT	 X X X	design welder X shop		
 C	VT MT PT RT UT	X X X X X	design welder X shop	Incorrect Profile 1. Excessive root penetration. 2. Travel speed too slow. 3. Excessive crown or reinforcement. 4. Incomplete root or negative root reinforcement or "suck back" (internal concavity). 5. Improper fillet contour usually wide on horizontal and not sufficient on vertical leg. 6. Incorrect electrode type.	1. Root opening too wide. 2. Welding current too high. 3. a. Welding speed too slow. b. Welding voltage too high arc length too long, correct arc length. 4. a. Voltage too high. b. Travel speed too fast. c. Root opening too wide. 5. Improper welding technique. Welding current too high. Reduce welding current. Use smaller electrode. 6. Use proper electrode type.
 D	VT MT PT RT UT	X X X X X	design welder X shop		

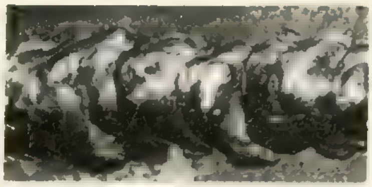
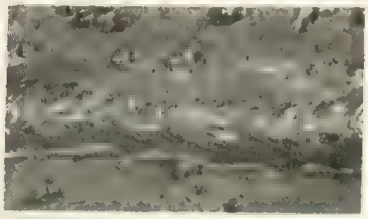
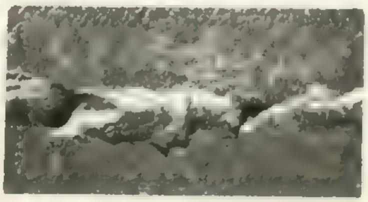
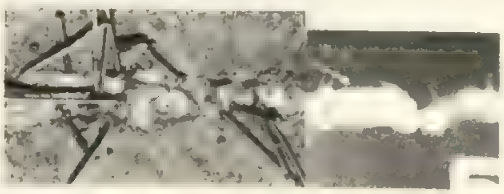
Weld Defect Class — Miscellaneous Defects Appearance or Cross Section or Radiograph Class No. 600	How Defected	Respon-sibility	Probable Cause	Corrective Action
	VT X MT PT RT X UT	design welder X shop	Poor Appearance 1. Welding current too high or too low. 2. Improper technique. 3. Faulty electrode. 4. Irregular travel speed.	1. Use prescribed procedure. 2. Provide additional welding training. 3. Use fresh electrod[e] determine correct t[ype] to be used. 4. Allow for additiona[l] practice and experien[ce]
	VT X MT PT RT UT	design welder X shop	Excessive Weld Spatter 1. Arc blow—see welding current. 2. Excessive welding current for type and size electrode. 3. Excessive long arc—high voltage. 4. Improper electrode type.	1. Reduce arc blow—u[se] alternating current 2. Adjust for proper we[lding] current for size ele[ct]rode used. 3. Hold proper arc leng[th] and use correct arc voltage. 4. Utilize proper electro[de] type for location
	VT X MT PT RT X UT	design welder X shop	Poor Tie-In 1. Incorrect electrode angle. 2. Improper technique for restriking arc.	1. Use correct electrode angle. Imrpove trainin[g]. 2. Provide additional tra[in]ing and experience
	VT X MT PT RT X UT	design welder X shop X	Whiskers 1. Root opening too wide.	1. Use correct root op[ening]. Use weaving motion [and] direct arc on weld pu[ddle]

FIGURE 22-47 Collection of weld defects: miscellaneous.

type of defect in this classification is *arc strikes*, which are unacceptable in certain types of work. These are defects where the welder accidentally struck the electrode on the base metal adjacent to the weld. This creates problems particularly on hardenable steel and on critical types of applications and is not acceptable. For certain types of work protective wrappings are made around the part, especially pipe adjacent to the weld, to avoid stray arc strikes. *Excessive spatter* adjacent to the weld is also a defect and is unacceptable. This may be caused by arc blow, by the selection of the incorrect electrode or welding current, or the technique of the welder. There are several other types of miscellaneous defects and those defects that apply specifically to particular processes are covered in the examples shown in Figure 22-47.

The above explanation and illustrations of different weld defects are based on opinions of various experts in the welding industry. Unfortunately, it is not universally possible to indicate which are acceptable and which are unacceptable. Some defects can be critical under certain service conditions or on specific metals. The same defect on less demanding service on mild steel would be acceptable. There is no common agreement as to what is acceptable and unacceptable in different types of service.

22-5 WORKMANSHIP SPECIMENS AND STANDARDS

A *workmanship specimen* is an actual weld with each weld bead showing for a short length. Such a specimen provides the welder with an example of what is expected and also gives the welding supervisor and the inspector an example. Figure 22-48 shows a vertical up V-groove weld made of medium thickness plate. The workmanship specimen is a quality control tool and also an instruction device. The workmanship specimen concept originated with the U.S. Army Ordnance Department to ensure the quality of weldments produced during World War II. Workmanship specimens were made for each of the weld

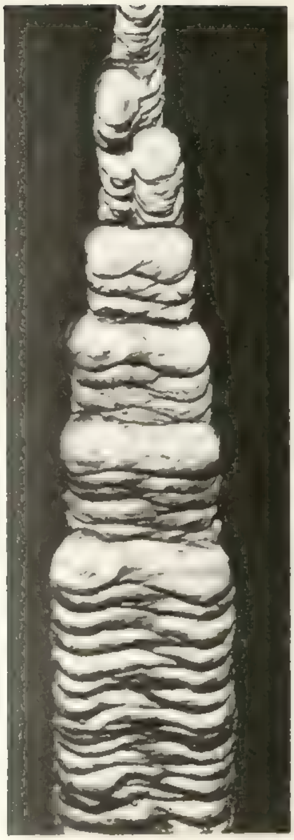


FIGURE 22-48 Workmanship specimen: vertical up SMAW

joints of an ordnance weldment. Cross-sectional samples were cut from the weld joint, polished, etched, and tack welded to the specimen to provide additional information. A weld schedule or procedure chart which shows the welding joint design, welding conditions, current, voltage, and so on, for each layer of the particular joint made. The schedules were followed in making the specific workmanship specimens. This technique provides a good tool for quality control. The information should be posted and made available to welders, welding supervisors, inspectors, engineers, and others at the point where the welding is done. Workmanship specimens can be made for any weld joint welded in any position using any of the arc welding processes. The principle is to show the joint fitup detail and each bead or weld as it is made in producing the total weld joint.

Complete parts are sometimes used instead of welding drawings or blueprints in the manufacturing department. These welded parts sometimes are posted in the welding booth where that part is manufactured. For companies making relatively small parts on a production basis this is an excellent technique of informing the welder and others of exactly the type of welds expected on the finished weldment. Many times these parts are painted with the welds highlighted in a different color of paint to make them stand out. Welding schedule and weld size information can be posted adjacent to the weldment specimen.

The concept of workmanship specimens is used extensively by major structural steel contracting companies. Many of these companies operate erection crews in widely separated areas, yet expect to have welds made the same way by the different crews. These companies produce workmanship specimens and provide the welding schedules for producing these workmanship specimens. They go a step further, and run qualification tests on each of the different joints that are normally employed.

The tail of the arrow of the welding symbol will show a specific joint detail specification. This detail specification will refer to a particular weld schedule and workmanship specimen that has been qualified in accordance with the code. By this means, the welding crew will always make the weld joint in the same manner and will utilize the procedure that is known to produce quality welds. This assists in consistency of welding but also in consistency of weld quality and further provides cost control since the weld joint is always made the same way. Figure 22-49 shows a typical welding specimen and the test bars produced from the specimen. The schedule for making this weld is shown in Figure 22-50.

Companies producing fairly heavy weldments can also use workmanship specimens but in these cases they may only show the different joints in a small section. These joints serve to show a proper way for making a particular weld, and also provide the appearance expected for making these welds. Companies that manufacture construction equipment often use these types of welding workmanship specimens.

Other companies have used the same concept to produce examples of welds that are acceptable and unacceptable. Originally the construction equipment company produced good and questionable welds of different types and posted the actual welds in the manufacturing department. However, they found that there was sufficient variation in the different specimens to create confusion. To overcome this, they produced one set of acceptable welds and one set of unacceptable welds and then made plastic replicas of each weld from these molds. The plastic weld replicas were posted in the department and in this case each and every impression was identical. Figure 22-51 shows the plastic replicas of acceptable and unacceptable welds. These types of exhibits are also very useful in the training of welders. The Department of Defense has used a similar technique with the military specification, which covers the smoothness of flame-cut surfaces. To actually portray the surface as expected and surfaces not acceptable, they have made a plastic replica of the actual flame-cut surfaces. This is reproduced and is a part of a military specification (Figure 22-52). For the purpose of welder training, workmanship specimens have been used and specimens have been developed that include typical problem areas for training welders. Some of the

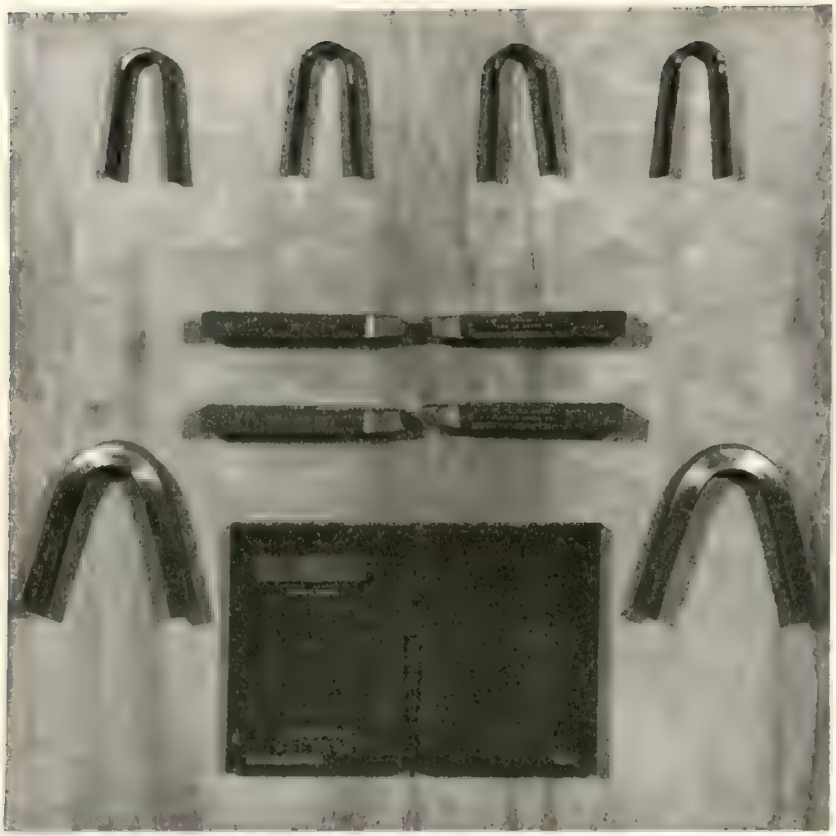


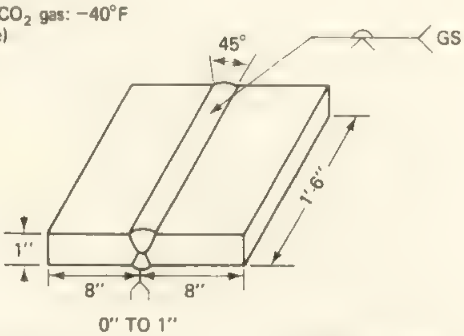
FIGURE 22-49 **Workmanship specimen and test bars.**

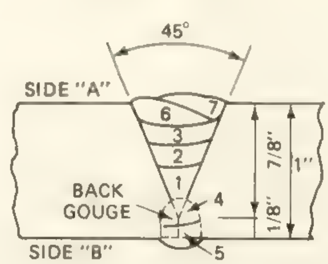
FIGURE 22-50 **Welding schedule for workmanship specimens.**

APPLICABLE SPECIFICATIONS: 1) See Sheet No. PQ-1 2) 3)	THE ABC STRUCTURAL COMPANY PROCEDURE SHEET FOR QUALIFICATION OF WELDING PROCEDURE WELD PROCEDURE: GS-B SV2 PROCEDURE SHEET TITLE: –WELDING PROCEDURE–	SHEET NO.: PQ-3 FILE NO.: PQ/GS

Base metal: ASTM A441
Fit-up: as shown
Preheat: none
Post heat: none
Dew point of CO_2 gas: −40°F (welding grade)

Welding gas shielded metal arc
Process: CO_2 gas; flux cored wire
Welding machine: semi-automatic
Welding position: flat

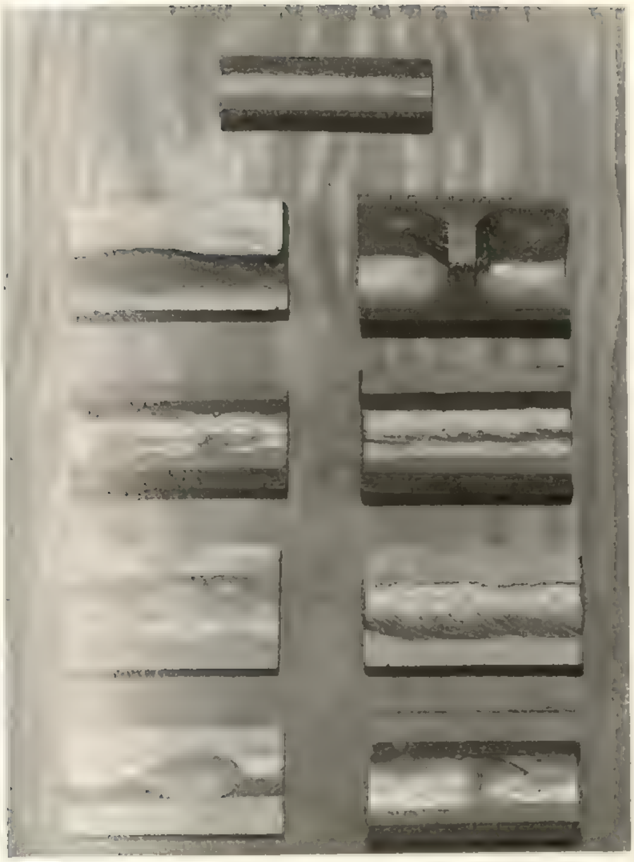




Pass sequence

SIDE	PASS NO.	SIZE	–ELECTRODE– TYPE	STICKOUT	POWER SOURCE	AMPS	VOLTS	TRAVEL SPEED (INS./MINUTE)	GAS FLOW
A	1 2 AND 3	3/32 3/32	FabCO 71 FabCO 71	1-1-1/4" 1-1-1/4"	DC+ DC+	475 475	30 30	13 10	45-50 C.F.H.
Turn plate over and back gouge to sound metal									
B A	4 AND 5 6 AND 7	3/32 3/32	FabCO 71 FabCO 71	3/4-1" 3/4-1"	DC+ DC+	475 475	30 30	12 13	

JOB NO.	DATE (ISSUED):	ISSUED BY: WELDING ENGINEERING DEPARTMENT



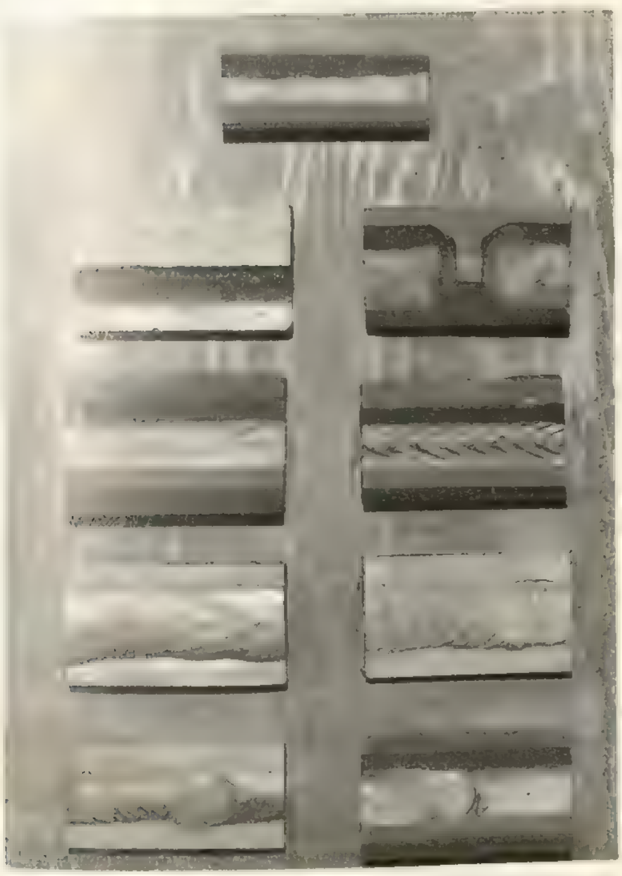


FIGURE 22-51 Plastic replicas of acceptable and unacceptable welds.

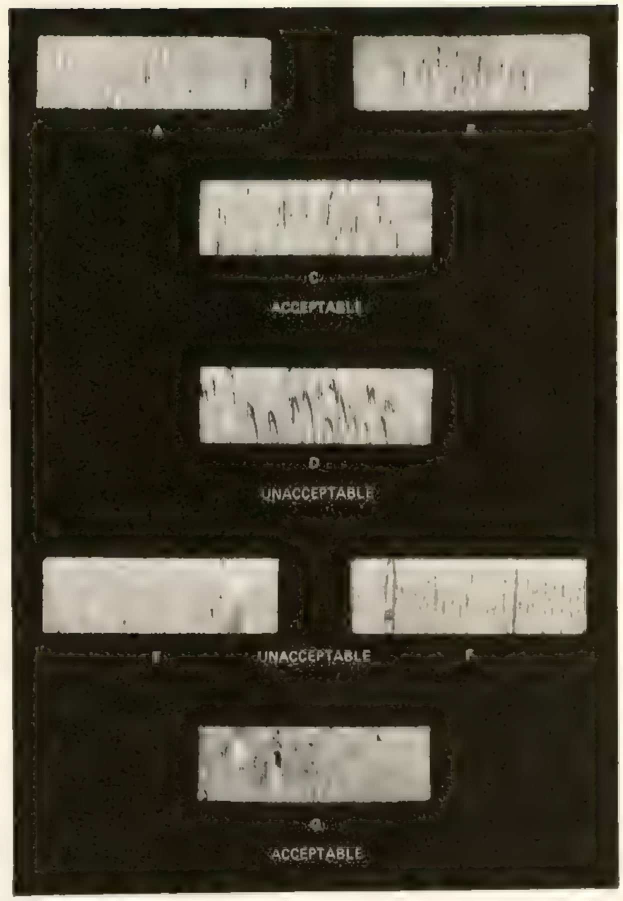


FIGURE 22-52 Plastic replicas of flame-cut surfaces. (From Ref. 8.)

problem areas are welding into and out of corners, changing electrodes, and making fillet welds on outside corners. These welding problems can be put together into one workmanship specimen and displayed in the welding department. The automotive industry uses a similar approach for controlling the weld quality on automobile frames. The frame design of different automobiles is usually different; however, the welding involved is similar. To provide control, a workmanship specimen display has been made and posted in the department. Figure 22-53 is a typical display to assist welders, supervisors, and inspectors in producing the types of welds required for this application.

The use of *workmanship standards* is another technique for maintaining weld quality and can be used as a quality control tool. Workmanship standards are a list of requirements that should be followed in producing quality weldments. A list of 20 requirements has been compiled and is shown in Figure 22-54. This list was made by reviewing the major welding codes and specifications and adopting those rules that repeat in the different codes. In many cases, welding codes and specifications are written in legal terms that may not be easily understood by welders. In compiling these 20 requirements an effort has been made to utilize terminology more understandable

FIGURE 22-53 **Automobile frame welding requirement.**

SPECIFICATION OF FILLET ARC WELDS FOR PASSENGER CAR FRAME FABRICATION

THIS SPECIFICATION IS ISSUED TO DEFINE THE QUALITY LEVEL OF FILLET WELDS IN ORDER THAT THE REQUIRED WELD QUALITY IN MILD STEEL MAY BE DISIGNATED TO INSURE PROPER PERFORMANCE OF EACH AND EVERY INDIVIDUAL PASSENGER CAR FRAME WELDMENT. ALL FILLET WELDS IN THIS SPECIFICATION WILL BE MADE WITH 60,000 P.S.I. MINIMUM FILLER METAL

DEFINITIONS

GAP (G)

THE DISTANCE BETWEEN TWO BASE METAL COMPONENTS AT THE ROOT OF THE JOINT TO BE WELDED.

MATERIAL THICKNESS—T_1-T_2

T_1—THINNER MATERIAL IN WELD JOINT
T_2—THICKEST MATERIAL IN WELD JOINT

FILLET WELD

A WELD OF APPROXIMATELY TRIANGULAR CROSS SECTION JOINING TWO SURFACES APPROXIMATELY AT RIGHT ANGLES TO EACH OTHER IN A LAP JOINT, TEE JOINT, OR CORNER JOINT.

WELD LENGTH

WELD LENGTH SPECIFIED ON THE ENGINEERING DRAWING REFERS TO THE MINIMUM EFFECTIVE DIMENSION. EFFECTIVE LENGTH IS MEASURED WHERE THE FILLET MEETS THE MINIMUM THROAT DIMENSIONS LISTED UNDER JOINT CHARACTERISTICS. WELD ARC STARTING OR FINISHING LOSSES ARE NOT INCLUDED IN THE EFFECTIVE LENGTH.

SIZE OF FILLET WELD

THE LEG LENGTH OF THE LARGEST ISOCELES RIGHT TRIANGLE WHICH CAN BE INSCRIBED WITHIN THE FILLET WELD CROSS SECTION.

THROAT OF A FILLET WELD (TH)

THE SHORTEST DISTANCE FROM THE ROOT OF A FILLET WELD TO ITS FACE.

UNDERCUT

A GROOVE MELTED INTO THE BASE METAL ADJACENT TO A WELD AND LEFT UNFILLED BY WELD METAL.

SKIP

AN UNWELDED PORTION OF THE DESIGNATED WELD.

BURN THROUGH

AN UNFILLED HOLE MELTED COMPLETELY THROUGH THE BASE METAL BY THE HEAT OF THE WELDING ARC.

SLAG INCLUSION

NON-METALLIC SOLID MATERIAL ENTRAPPED IN THE WELD METAL OR BETWEEN WELD METAL AND BASE METAL.

VISIBLE POROSITY

GAS POCKETS OR VOIDS IN THE WELD DEPOSIT EXPOSED TO THE WELD SURFACE NOT GREATER THAN 1/16" DIAMETER.

CRATER

A DEPRESSION AT THE TERMINATION OF A WELD BEAD.

CRACK

A BREAK OR RUPTURE APPEARING IN THE WELD DEPOSIT OR ADJACENT TO THE WELD JUST AFTER WELD HAS COOLED TO ROOM TEMPERATURE

WORKMANSHIP SAMPLES

WELD QUALITY WILL BE JUDGED ON DIMENSIONAL AND VISUAL APPEARANCE CONSIDERATIONS AS DEFINED BY THIS SPECIFICATION. WORKMANSHIP SAMPLES WHICH SHOW EXAMPLES OF ACCEPTABLE QUALITY WELDS SHALL BE RETAINED AT THE MANUFACTURING SOURCE.

JOINT CHARACTERISTICS

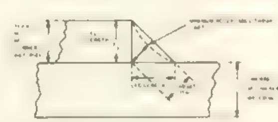
FILLET SIZE

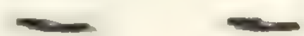
THE WELD LEG LENGTH OF EACH SIDE OF THE JOINT SHALL BE EQUAL TO THE THICKNESS OF THE THINNER MATERIAL BEING WELDED. WHERE GAPS ARE PRESENT IN THE WELD JOINT, THE LEG LENGTH ON BOTH LEGS OF THE WELD MUST BE INCREASED BY THE WIDTH OF THE GAP, AND THROAT REQUIREMENTS WILL BE PROPORTIONATELY INCREASED.

T_1 = THICKNESS OF THINNER STOCK
G = WIDTH OF GAP
LEG LENGTH = T_1 + G
(WHEN GAP IS PRESENT)

SATISFACTORY — SATISFACTORY WITH GAP — UNSATISFACTORY WITH GAP

MINIMUM THROAT OF THE FILLET WELD TO BE 0.60 OF THINNER MATERIAL BEING JOINED.





SATISFACTORY THROAT - 0.61T — UNSATISFACTORY THROAT 0.50T

MAXIMUM ALLOWABLE UNDERCUT OF BASE METAL

UNDERCUTTING WILL BE PERMITTED PROVIDED THAT IT DOES NOT EXCEED A DEPTH 10% OF THE THINNER STOCK THICKNESS WITHIN 1/2" OF THE EXTREMITIES OF THE WELD, AND THAT THE DEPTH OF THE UNDERCUT DOES NOT EXCEED AN AVERAGE OF 15% OF THE THINNER STOCK THICKNESS ON EITHER TOE OVER THE BALANCE OF THE WELD, NOR REACH A DEPTH EXCEEDING 30% OF THE THINNER STOCK THICKNESS AT ANY POINT

SATISFACTORY
AVERAGE UNDERCUT - 15%
MAXIMUM UNDERCUT - 30%

UNSATISFACTORY
AVERAGE UNDERCUT 22%
MAXIMUM UNDERCUT 26%

BURN THROUGHS

NONE PERMITTED

UNSATISFACTORY

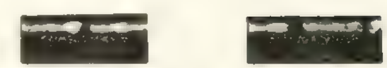
VISIBLE POROSITY

SCATTERED SURFACE POROSITY WILL BE TOLERATED PROVIDED IT DOES NOT EXCEED AN AVERAGE OF ONE PIN HOLE PER INCH OF WELD NOR MORE THAN THREE PIN HOLES IN ANY ONE INCH OF WELD. THE LARGEST PIN HOLES SHALL BE NO GREATER THAN 1/16" IN DIAMETER.

SATISFACTORY — UNSATISFACTORY

ALLOWABLE SKIPS OR SLAG INCLUSIONS

ONE 3/8" DEFECT PERMISSIBLE IN ANY 4" OF WELD.



SATISFACTORY — UNSATISFACTORY

PRESENCE OF CRACKS

NONE ALLOWED

Every welder is responsible for welding done. The following workmanship standards must be followed in order to produce high quality welds. They may be employed as a company standard. (Specific codes or specifications take priority over these standards.)

1. Surfaces to be welded must be reasonably free from scale, paint, grease, water, etc.
2. When it is necessary to trim adjacent parts for proper fit-up, the designed bevel and root opening must be maintained. Trim to provide designed weld grooves.
3. Where the clearance between members to be joined in a T type joint is greater than 1/16" the size of the fillet weld shall be the size specified plus the amount of the gap.
4. Preheat or interpass temperature requirements must be adhered to.
5. The specified electrode or electrode matching the base metal must be used.
6. Welding procedures must be followed explicitly. This means using the correct welding electrode type, and size, the proper preheat and interpass temperature and compliance with any specific insturctions with regard to the joint or weldment.
7. Cracked or defective tack welds must be removed before weld is made.
8. Cracked or welds having surface irregularities must be repaired before welding continues.
9. Welds showing excessive, surface porosity must be removed and rewelded.
10. All weld craters shall be completely filled before depositing the next weld bead or pass.
11. Each bead or pass of a multi-pass weld must be cleaned before the next bead is made.
12. The specified size and length of weld as shown on blueprint and drawings, is the minum acceptable. Weld size tolerances should be + 1/6" – 0.
13. Weld reinforcement or crown shall not exceed 1/16" for manual welds.
14. Under-cut is not permissible on highly stressed or dynamically loaded members.
15. Root fusion must be complete on all joints designed with a root opening. This applies whether a backing strip is, or is not, employed.
16. Welds showing subsurface slag or voids, by nondestructive inspection, must be gouged out to sound metal and rewelded. Small amounts of slag or small voids may be permitted.
17. Welds showing subsurface cracks by NDT must be gouged out to sound metal and rewelded.
18. All work should be positioned for flat position welding whenever possible.
19. Weldments or specific welds may be taken at random and submitted to a 100% visual inspection or to any of the nondestructive testing methods to determine weld quality.
20. Welders may be required to requalify if in the opinion of the inspector and the supervisor the work is of questionable quality.

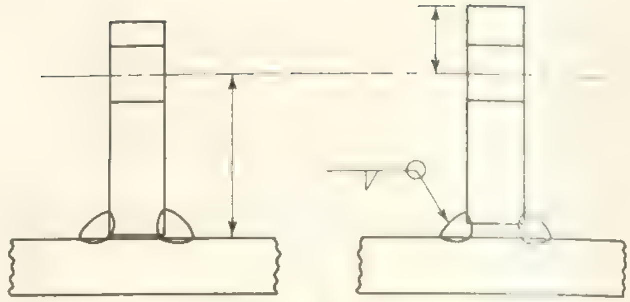
FIGURE 22-54 **Workmanship standards.**

by welders. The result of this is a collection of 20 rules that can and should be used when a code is not involved. It is suggested that companies that do not utilize established codes adopt these 20 requirements as their own company standard. The basis for this standard is stated in the first sentence. "Welders are responsible for their own work."

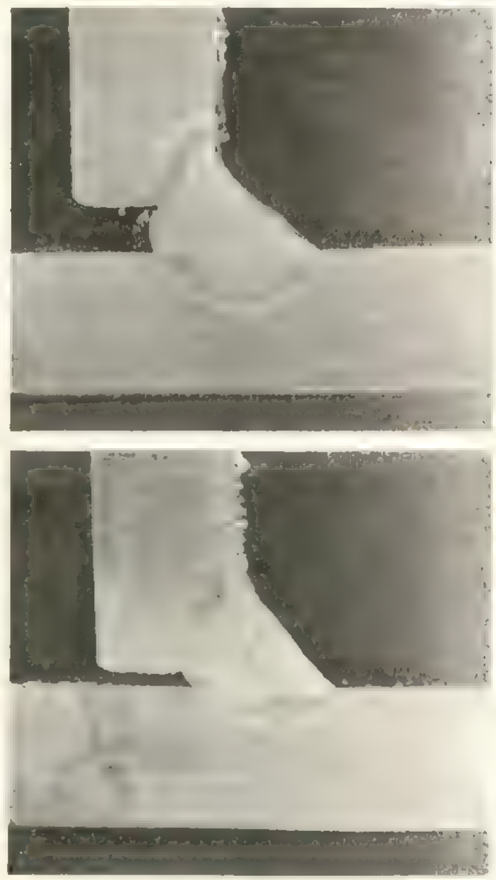
1. "Surfaces to be welded must be reasonably free from scale, grease, paint, water, etc." This is qualified by the word *reasonably* to allow welders and inspectors to exercise judgment. For example, mill scale on new steel just received is usually tight and it would be needless to remove mill scale from new steel; however, if the steel has excessive mill scale or rust it should be removed. The basis here is to provide a good surface for welding. This is good practice and is mentioned in most codes. The surface must be sufficiently clean so that there is nothing that might contain hydrocarbons, which break down in the heat of the arc providing hydrogen which can be absorbed in the weld and cause cracks. Welding over paint is a special case and is discussed elsewhere.
2. "If it is necessary to trim adjacent parts for proper fitup, the designed bevel and root opening must be maintained." Too often tolerances accumulate when setting up a weldment and these are absorbed

in weld joints. This can eliminate root openings so that incomplete penetration will result. On the other hand, it can result in excessively large gaps which will require too much weld metal to make the joint and may also introduce undesired warpage. Welders should be cautioned to review the requirements of the weld joint and take corrective action when required if the joint is not as designed.

3. "Where the spacing between members to be joined by a T-type fillet welded joint is greater than $\frac{1}{16}$ in. (1.6 mm), the size of the fillets should be the size specified plus the amount of the opening." This is best shown in Figure 22-55. The problem involved here is the fact that a weld fillet size as specified can be made and the inspection after the weld is made would indicate that it is acceptable. However, in view of the opening between the parts, the effective, or failure, area of the fillets would be much less than designed. This type of problem is relatively common, particularly when small fixtures are used to locate premachined parts such as lugs, gussets, etc. Premature failure can occur, particularly if these lugs are loaded-carrying parts.
4. "The preheat or interpass temperature specified must be adhered to." This is obvious, but it is occasionally ignored. Or, it may be that the preheat is only a surface heat instead of a through heat. If at all possible the temperature of the part should be checked on the side opposite that to which heat is being applied. Specifications recommend a soak type of heating, not merely a surface heating, which would rapidly disappear as soon as the heat source is removed.
5. "The specified electrode and electrodes matching the base metal must be used." This is an obvious requirement but one that may be ignored. On some weldments two, three, or more types of electrodes may be employed. It is extremely important that the proper electrode or filler metal be used where specified. The quality of deposited weld metal from different shielded metal arc welding electrodes varies and the properties may not be satisfactory for the service life. For example, the electrode that would be used for welding sheet metal guards or guard rails is not proper for welding major joints of heavy thickness.
6. "The written welding procedure provided must be followed explicitly." This is an obvious requirement; however, in construction jobs and in large manufacturing plants often the written procedures are not available to the welders making the weld. The cost of producing written procedures and especially qualified procedures can be quite expensive. It is prudent to provide specialized information and it must be followed.
7. "Cracked or defective tack welds must be removed before the weld is made." This is an obvious instruction; however, one that is ignored quite often. Tack welds frequently crack. They crack because they are small with respect to the loads that can be imposed on them. Some welders feel that they have sufficient skill to burn through or melt out a cracked tack weld. This may be so, but the average welder normally does not have this skill and the crack is



(a)



(b)

FIGURE 22-55 Equal-size fillets with different strength.

still in the final weld where it can cause problems or will be detected by NDT techniques.

8. "Cracked welds or welds having surface irregularities must be repaired before welding is continued." An obvious requirement, but one sometimes ignored with the feeling that the crack or the irregular weld metal can be covered up with the next pass or bead. This might be so, but it is poor practice since the crack is still in the weld joint and may propagate and create problems later or will be detected by NDT techniques. The best policy is to repair a weld at its earliest possible time of repair.
9. "Welds showing excessive surface porosity must be removed and rewelded." Again, an obvious instruction. Surface porosity is usually an indication that there is subsurface porosity. For this reason, porous welds should be removed and a determination made if sub-surface porosity occurs. The cause of the porosity should be corrected before welding continues.
10. "All weld craters should be completely filled before depositing the next weld bead or pass." A crater is the depression at the end of the weld. However, if welding is to be immediately continued, after changing an electrode, the crater may be allowed to stay, provided that it is filled quickly with the next electrode when the bead is continued. If the crater is at the end of a weld or at a change of direction or at a corner it must be filled. This is a matter of technique and can be done by the welder by hesitating shortly before breaking the arc. Craters are prone to produce cracks which might propagate and reduce the service life of the weldment.
11. "Each bead or pass of multipass welds must be cleaned before the next bead is made." This requirement is primarily for the shielded metal arc welding process. It applies also to submerged arc welding and flux-cored arc welding. It is important to remove the slag since it can be trapped in an undercut area and will reduce the strength of the joint. Entrapped slag will be detected by x-ray or other NDT tests. In the case of horizontal multipass fillets judgement can be exercised and cleaning may not be required if in the opinion of the inspector the welder has sufficient skill to avoid entrapping the slag.
12. "The specified size and length of welds as shown on blueprints and drawings is the minimum acceptable. Weld size tolerances should be -0 and + 1/16 in. (1.6 mm)." This is important since many drawings have standardized tolerances printed on the drawing form. Such standardized statements might state that all fractional dimensions must be + or − 1/16 in. or similar. Assuming that there are many 3/16 in. fillets, this would mean that fillet welds could all be 1/8 in. which would in effect greatly weaken them. It is necessary to review such standardized statements and modify them if they could be interpreted to involve dimensions on welds (see Figure 22-55).
13. "Weld reinforcement or crown should not exceed 1/16 in. (1.6 mm) for manual welds or 1/8 in. (3.2 mm) for automatic welds." There are several reasons for this requirement. The most important is that the extra reinforcement is an economic waste since it is not required. Second, some welders may put extra reinforcement on a weld to camouflage internal flaws they may know about in a groove weld. Additionally, extra reinforcement causes stress concentration since the stresses will spread to occupy the entire cross section. If the toe of the weld or the edge of the reinforcement is abrupt this can create a concentraion. Finally, it is absolutely unnecessary for mild steel and low-alloy steels; the weld metal is stronger because it has a higher yield strength than the base metal.
14. "Undercut is not permissible on highly stressed or dynamically loaded members." Undercut is a defect that is not allowed by most codes. Some codes allow a small amount of undercut, provided that it is within specified limits. Undercut areas tend to concentrate stresses and will in time create field problems. This can occur on both tensile and compressive loaded weld joints.
15. "Root fusion must be complete on all joints designed with a root opening. This applies whether a backing strip is or is not employed." Root fusion is absolutely necessary for any weld with a root opening. The root face of both sides of the joint must be fused into the weld. It is also the reason why NDT technique is used for root pass inspection.
16. "Welds showing subsurface slag or voids by nondestructive testing must be removed to solid metal and rewelded. Small amounts of slag or voids may be permitted." Some codes do allow small amounts of slag or porosity provided they are small and not continuous. Usually, slag and porosity voids have rounded edges and will not propagate under designed loads.
17. "Welds showing subsurface cracks by nondestructive testing must be removed to sound metal and rewelded." In this case the requirement is absolutely necessary since cracks have sharp corners or sharp ends and do propagate under load. They are stress risers and will cause premature failure or shortened

service life. Internal cracks are not acceptable by any of the major codes.

18. "All work should be positioned for flat-position welding whenever possible." This is good economical practice. A welder who is working in a comfortable position will produce higher-quality welds.

19. "Weldments or specific welds can be taken at random and submitted to 100% visual inspection or to any of the nondestructive testing methods to determine weld quality." This rule and the next are provided to give the inspector the necessary authority that is needed to maintain quality.

20. "Welders may be required to requalify if in the opinion of the inspector and the welder's supervisor the work produced is of questionable quality." Quite often a welder's work may deteriorate for one reason or another. This rule provides the mechanism of having the welder retested to determine the cause of the problem. This can be a temporary problem or a problem correctible by training or by improved eyesight, etc. This is a tool that the inspector can use whenever a questionable weld quality situation results from the work of a specific welder.

Companies that are not required to produce weldments by a national code should adopt a set of workmanship standards similar to the above. This will provide a better understanding between the designer, the welder, the welding supervisor, and the inspector to maintain weld quality.

22-6 NONDESTRUCTIVE EXAMINATION SYMBOLS

Nondestructive examination symbols have been established by the American Welding Society.[9] They are used by the designer to convey information to the inspector concerning joints, welds, or weldments that need special attention. These symbols are very similar to welding symbols and can be used in conjunction with welding symbols. Figure 22-56 shows the elements of the examination symbol and the standard location with respect to each other and only those elements required to provide the needed information are used. The examination symbol or disignated letters are shown in Figure 22-57. One special symbol is used to show the direction of radiation which is used in conjunction with the radiographic examination symbol (Figure 22-58). Typical testing symbols are shown in Figure 22-59. For complete information on nondestructive examination symbols it is recommended that the reader consult the AWS standard.

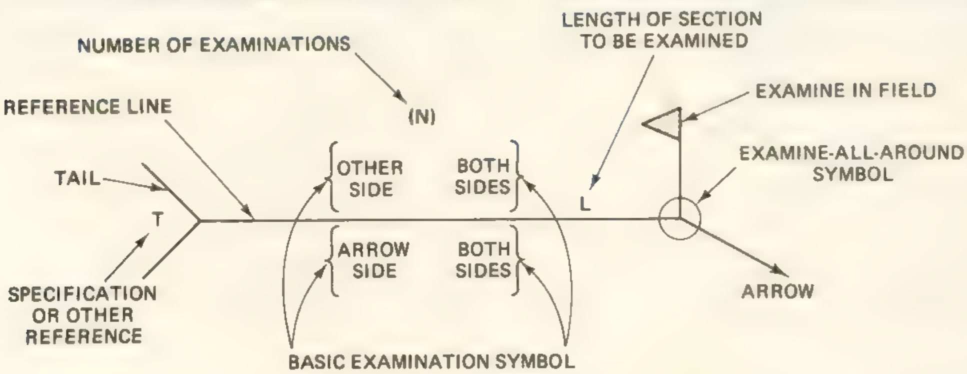
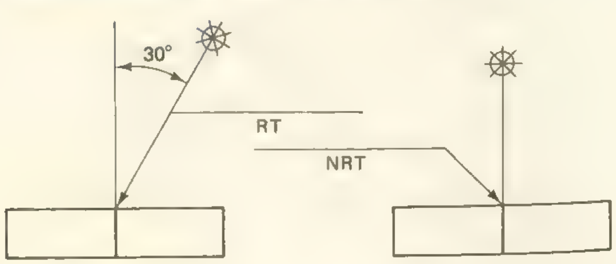


FIGURE 22-56 Standard location of elements.

FIGURE 22-57 Examination methods: letter designation.

Examination Method	Letter Designation
Acoustic emission	AET
Electromagnetic	ET
Leak	LT
Magnetic particle	MT
Neutron radiographic	NRT
Penetrant	PT
Proof	PRT
Radiographic	RT
Ultrasonic	UT
Visual	VT

FIGURE 22-58 Radiation location symbol.



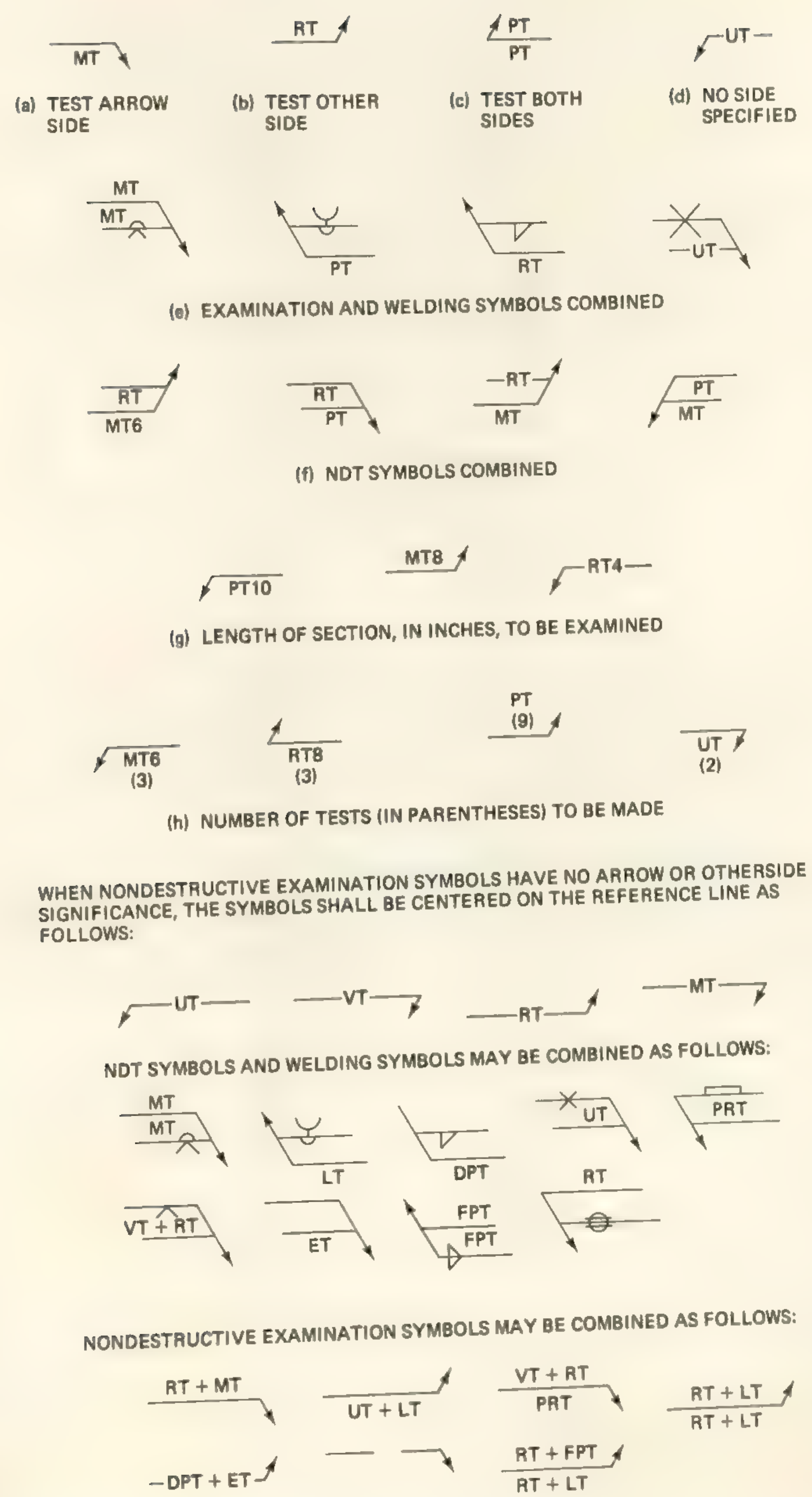


FIGURE 22-59 Typical examination symbols.

QUESTIONS

22-1. What is a destructive test? When are destructive tests used?

22-2. What is the difference between a root bend, a face bend, and a side bend test? When is the side bend test used instead of root or face bent tests?

22-3. When is a fillet break test used?

22-4. What is different about the guided bend test jig for testing ⅜-in. specimens or 1- in. specimens?

22-5. What is the reason for the 0.505-in. diameter of tensile test specimen?

22-6. What is the most widely used nondestructive evaluation technique? What are its three divisions?

22-7. Explain the use of a fillet weld gage. Show typical fillet size problems.

22-8. Does AWS qualify and certify welding inspectors? How is this done?

22-9. Explain the principle of dye-penetrant testing. What are its limitations?

22-10. Can penetrant testing be used on plastic parts?

22-11. Explain the principle of magnetic particle testing. Why is it not used on aluminum?

22-12. Is ac or dc current used for MT examinations?

22-13. Explain the principle of radiographic testing. How are radiographs developed?

22-14. What is a penetrameter? Explain.

22-15. Can permanent records be made of UT results?

22-16. Explain the principle of ultrasonic testing. Can it be used for field inspection?

22-17. Why is leak testing with compressed air dangerous?

22-18. Name the six classes of defects.

22-19. Why are cracks more dangerous than porosity to weld service life?

22-20. Can testing symbols be combined with weld symbols?

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3. "Guide for the Nondestructive Inspection of Welds", AWS B1.10, American Welding Society, Miami, Fla.
4. "IIW Collection of Reference Radiographs of Welds," American Welding Society, Miami, Fla.
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7. "Welding Inspection," American Welding Society, Miami, Fla.
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23

Welding Problems and Solutions

OUTLINE

23-1 ARC BLOW

Arc blow is the deflection of an electric arc from its normal path because of magnetic forces. Deflection of the arc, or blow, as it is called, can be extremely frustrating to a welder. It will usually adversely affect the appearance of the weld, will cause excessive spatter, and can also impair the quality of the weld. It is well known to the welder using the shielded metal arc welding process with covered electrodes. It is also a factor in semiautomatic and fully automatic arc welding processes. Arc blow occurs primarily when welding steels or ferromagnetic materials but it can also be encountered when welding nonmagnetic materials. The welding arc is usually deflected forward or backward of the direction of travel; however, it may be deflected from one side to the other. It can become so severe that it is impossible to make a satisfactory weld. Arc blow is one of the most troublesome problems encountered by the welder and one that is the least understood.[1]

The laws of electricity and magnetism can help explain the problem of arc blow. When an electric current passes through an electrical conductor it produces a magnetic flux in circles around the conductor in planes perpendicular to the conductor and with their centers in the conductor. The *right-hand rule* is used to determine

the direction of the magnetic flux. It states that when the thumb of the right hand points in the direction in which the current flows (conventional flow) in the conductor, the fingers point in the direction of the flux. The direction of the magnetic flux produces polarity in the magnetic field, the same as the north and south poles of a permanent magnet. This magnetic field is the same as produced by an electromagnet. The rules of magnetism which state that like poles repel and opposite poles attract apply in this situation. Welding current is much higher than the electrical current normally encountered. Similarly, the magnetic fields are much stronger.

The welding arc is an electrical conductor and the magnetic flux is set up surrounding it in accordance with the *right-hand rule.* The important magnetic field in the vicinity of the welding arc is the field produced by the welding current which passes through it from the electrode and to the base metal or work. This is a self-induced circular magnetic field which surrounds the arc an exerts a force on it from all sides according to the electrical-magnetic rule. As long as the magnetic field is symmetrical, there is no unbalanced magnetic force and there is no arc deflection. Under these conditions the arc is parallel or in line with the centerline of the electrode and it takes the shortest path to the base plate. If the symmetry of this magnetic field is disturbed, the forces on the arc are no longer equal and the arc is deflected by the strongest force.

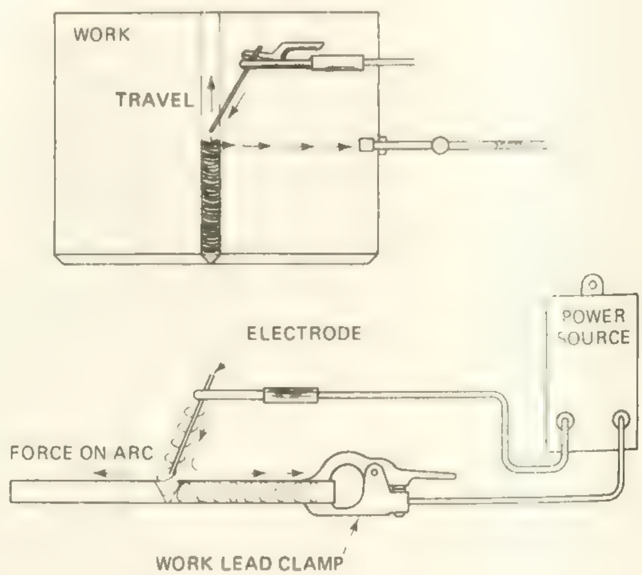
This electrical-magnetic relationship is used in certain welding applications for magnetically moving or oscillating the welding arc. The gas tungsten arc is rather easily deflected by means of magnetic flux. It can be oscillated by transverse magnetic fields or it can be made to deflect in the direction of travel. To move the arc magnetically is to rely on the flux field surrounding the arc and to move this field by introducing an external-like polarity field. Oscillation is obtained by reversing the external transverse field to cause it to attract the field surrounding the arc. As the self-induced field around the arc is attracted and repelled, it tends to move the arc column, which tries to maintain symmetry within its own self-induced magnetic field. Magnetic oscillation of the gas tungsten welding arc is used to widen the deposition. Arcs can also be made to rotate around the periphery of abutting pipes by means of rotating magnetic fields. Longer arcs are more easily moved than short arcs. The amount of magnetic flux to create the movement must be of the same order as the flux field surrounding the arc column. This is done purposely and mentioned here only to describe the use of magnetic fields and their relationships to arcs.

The preceding data are helpful in explaining the phenomena of magnetic arc blow. Whenever the symmetry of the field is disturbed by some other magnetic force, it will tend to move the self-induced field surrounding the arc and thus deflect the arc.

Except under the most simple conditions, the self-induced magnetic field is not symmetrical throughout the entire electric circuit and changes direction at the arc. Furthermore, there is always an unbalance of the magnetic field around the arc because the arc is moving and thus the current flow pattern through the base material is not constant.

There is another factor that helps produce the non-symmetrical or unbalanced relationship of the magnetic forces. The magnetic flux will pass through a magnetic material such as steel much easier than it will pass through air. In fact, the magnetic flux path will tend to stay within the steel and will be more cncentrated and stronger than in air. Welding current passes through the electrode lead, the electrode holder to the welding electrode, then through the arc into the base metal (assume steel). At this point the current changes direction to pass to the work lead connection, then through the work lead back to the welding machine (Figure 23-1). At the point the arc is in

FIGURE 23-1 Unbalanced magnetic force due to current direction change.

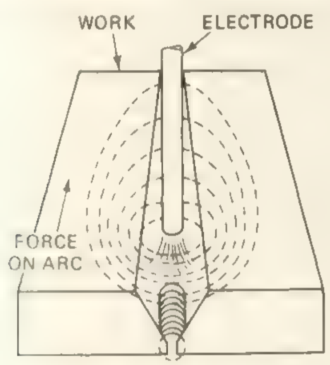


contact with the work, the change of direction is relatively abrupt, and the fact that the lines of force are perpendicular to the path of the welding current creates a magnetic unbalance at this point. The lines of force are concentrated together on the inside of the angle of the current path through the electrode and the work and are spread out on the outside angle of this path. Consequently, the magentic field is much stronger on the side of the arc toward the work lead connection than on the other side. This unbalance of magnetic forces produces a force on the stronger side which deflects the arc to the left. This is toward the weaker force and is opposite the direction of the current path. The direction of this force is the same

whether the current is flowing in one direction or the other. In other words, if the welding current is reversed the magnetic field is also reversed but the direction of the magnetic force acting on the arc is always in the same direction away from the path of the current through the work.

The second factor that keeps a magnetic field from being symmetrical is the fact that the arc is moving and depositing weld metal. As a weld is made joining two plates, the arc moves from one end of the joint to the other. The magnetic field in the plates will constantly change. If we assume the work lead is immediately under the arc and moving with the arc the magnetic path in the work will not be concentric about the point of the arc. This is because the lines of force do not take the shortest path but the easiest path. Near the start end of the joint the lines of force are crowded together since the lines of force will tend to stay within the steel. Toward the finish end of the joint the lines of force will be separated since there is more area (Figure 23-2). In addition, where the

FIGURE 23-2 Unbalanced magnetic force due to unbalanced magnetic path.

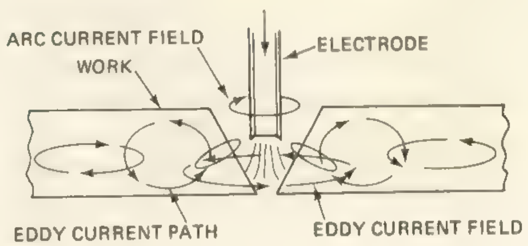


weld has been made the lines of force go through steel. Where the weld is not made the lines of force must cross the air gap or root opening. The magnetic field is more intense on the short end and the unbalance produces a force which deflects the arc to the right or toward the long end.

When welding with direct current the total force tending to cause the arc to deflect is a combination of these two forces. Sometimes these forces tend to add and sometimes they subtract from each other, and at times they may meet at right angles. The polarity or direction of flow of the current does not affect the direction of these forces nor the resultant force. By analyzing the path of the welding current through the electrode and into the base metal to the work lead, and analyzing the magnetic field within the base metal it is possible to determine the resultant forces and predict the resulting arc deflection or arc blow.

The use of alternating current for welding greatly reduces the magnitude of deflection or arc blow. Alternating current for welding does not completely eliminate arc blow. The reason for the reduction of arc blow is that the alternating current sets up other currents that tend to neutralize the magnetic field or greatly reduce its strength. Alternating current varies between maximum value of one polarity and the maximum value of the opposite polarity, and the magnetic field surrounding the alternating current conductor does the same thing. The alternating magnetic field is a moving field which induces current in any conductor through which it passes, according to one of the basic laws of electricity, the *induction principle*. This means that currents are induced in nearby conductors in a direction opposite to that of the inducing current. These induced currents are called eddy currents. They, in turn, produce a magnetic field of their own which tends to neutralize the magnetic field of the arc current. These currents are alternating currents of the same frequency as the arc current and are in the part of the work nearest the arc. They always flow from the opposite direction (Figure 23-3). When alternating current

FIGURE 23-3 Reduction of megnetic force due to induced fields.



is used for welding, eddy currents are induced in the workpiece, which produce magnetic fields which reduce the intensity of the field acting on the arc. Unfortunately, alternating current cannot be used for all welding applications and for this reason changing from direct current to alternating current may not always be possible to eliminate or reduce arc blow.

With an understanding of the factors that affect arc blow, it is now possible to explain the practical factors involved with arc blow and provide solutions for overcoming them. Arc blow is caused by magnetic forces. The induced magnetic forces are not symmetrical about the magnetic field surrounding the path of the welding current. One factor is the nonsymmetrical location of magnetic material with respect to the arc. This creates a magnetic force on the arc which acts toward the easiest magnetic path and is independent of electrode polarity. The location of the easiest magnetic path changes constantly as welding progresses; therefore, the intensity and the direction of the force changes.

The second factor is the change in direction of the welding current as it leaves the arc and enters the workpiece. Welding current will take the easiest path but not always the most direct path through the work to the work lead connection. The resultant magnetic force is opposite in direction to the current from the arc to the work lead connection. It is independent of welding current polarity.

The third factor explains why arc blow is much less with alternating current. This is because the induction principle creates current flow within the base metal, which creates magnetic fields, that tend to neutralize the magnetic field affecting the arc.

The greatest magnetic force on the arc is caused by the difference in resistance of the magnetic path in the base metal around the arc. The location of the work lead connection is of secondary importance but may not have an appreciable effect on reducing the total magnetic force on the arc. It is best to have the work lead connection at the starting point of the weld. This is particularly true in electroslag welding where the work lead should be connected to the starting sump. On occasion, the work lead can be changed to the opposite end of the joint. In some cases, leads can be connected to both ends.

The conditions that affect the magnetic force acting on the arc vary so widely that it is impossible to do more than make generalized statements regarding them. The following suggestions may help reduce arc blow under some conditions.

The magnetic forces acting on the arc can be modified by changing the magnetic path across the joint. This can be accomplished by runoff tabs, starting plates, large tack welds, and backing strips, as well as the welding sequence. An external magnetic field produced by an electromagnet may be effective. This can be accomplished by wrapping several turns of welding lead around the workpiece. Arc blow is usually more pronounced at the start of the weld seam. In this case a magnetic shunt or runoff tab will reduce the blow. In addition, it is always wise to use as short an arc as possible so that there is less of an arc for the magnetic forces to control.

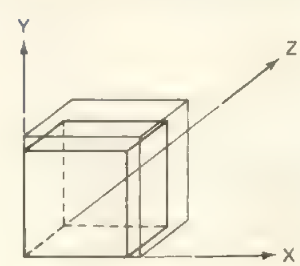
The welding fixture can be a source of arc blow; therefore, an analysis with respect to fixturing is important. The hold-down clamps and backing bars must fit closely and tightly to the work. In general, copper or nonferrous metals should be used. Magnetic structure of the fixture can affect the magnetic forces controlling the arc.

Another major problem can result from magnetic fields already in the base metal particularly when the base metal has been handled by magnet lifting cranes. Residual magnetism in heavy thick plates handled by magnets can be of such magnitude that it is almost impossible to make a weld. The solution here is to attempt to demagnetize the parts, wrap the part with welding leads to help overcome their effect, or, if all else fails, stress relieve or anneal the parts.

23-2 WELDING DISTORTION AND WARPAGE

Most of the welding processes involve heat. High-temperature heat is largely responsible for welding distortion, warpage, and stresses. When metal is heated it expands and it expands in all directions. When metal cools it contracts and again contracts in all directions. To understand this better, consider an extremely small piece of metal the shape of a cube (Figure 23-4). When it is exposed to a temperature increase it will expand in all three directions, the *x*, *y*, and *z* directions. There is a direct relationship between the amount of temperature change and the change in dimension. This is based on the coefficient of thermal expansion. This is a measure of the linear increase per unit length based on the change in temperature of the material. The coefficient of expansion is different for the various metals. Aluminum has one of the greatest coefficient of expansion ratios, and changes in dimension almost twice as much as steel for the same temperature change. The coefficient of expansion of the common metals is given in Figure 15-1. A metal expands or contracts by the same amount when heated or cooled the same temperature, if it is not restrained. This can be proved; take a straight wire and accurately measure its length cold, then heat it, and measure its length hot. Allow it to cool, measure it again, and notice that it has returned to the original length. Unfortunately, in the case of welding the metals that are heated and cooled are not unrestrained. They are restrained because they are a part of a larger piece of metal which is not heated to the same temperature. This pinpoints the problem. If we have uniform heating and unrestrained parts, the heating and cooling are relatively distortion free. In actual practice, particularly with respect to welding, the heating is rarely uniform across the cross section of a part. There is always restraint, because the parts not heated or heated to a lesser amount tend to restrain that portion of the same piece of metal that is heated to a higher temperature. This differential or nonuniform heating, which always occurs in welding, and the partial restraint resulting from the part's being nonuniformly heated is the principal cause for thermal distortion and warpage that occur in welding.

FIGURE 23-4 Cube of metal showing expansion.



The coefficient of expansion is an important factor when considering warpage. It is the factor responsible for the different degrees of warpage between different metals. Of the common structural metals, aluminum has the highest coefficient of expansion; it is approximately twice as great as plain carbon steel. This is significant when trying to relate the warpage that might occur when welding steel compared to when welding aluminum. The coefficient of expansion for steel is 6.7×10^{-6}; written out, this would be 0.0000067, which is the amount in inches that steel expands for every degree Fahrenheit the temperature rises. As an example, if a piece of steel is taken from 100 °F (38 °C) up to a dull red heat of, say, 1100° (593 °C), we would have a temperature change of 1000 °F (538 °C). Multiplying these two figures would show that there is a change in dimension per inch of 0.0067 in. (0.17 mm), or 6.7 thousandths of an inch. This may appear to be a relatively small change in dimension, but it is significant. If we would select aluminum for this same temperature change, the results would be larger. Aluminum has a coefficient of expansion of 13.8×10^{-6} in. per degree change of temperature. Again, if we expose it to 1000 °F (538 °C) change in temperature (which, incidentally would almost cause aluminum to melt), we would have a change of 0.0000138×1000, or a dimensional change of 0.0138 in (0.35 mm), which is a change of almost 1/64 in. (0.4 mm) per inch. To make this a little more meaningful, assume a 10-in. (250-mm)-long round rod. Each inch of the aluminum will expand the 0.0138 in. (0.035 mm), but the entire bar, which is 10 in. (250 mm) long, would expand 0.138 in. (3.5 mm) or slightly over 1/8 in. (3.2 mm), and this is certainly significant with respect to warpage.

In practical application, we do not have the free expansion and contracting and uniform heating. Consider a round rod placed in a vise or in some device that is absolutely unmovable (Figure 23-5A). With this rod in between two unmovable surfaces we will uniformly heat the bar 1000 °F (538 °C) or the difference above room temperature to, say, 1070 °F (577 °C). In the case of the steel bar it would try to expand 0.067 in. (1.7 mm) per inch, or in the case of aluminum would try to expand 0.138 in. (3.5 mm) per inch. However, the restraining surfaces will not move. In other words, the bar is restrained in its ability to expand in the length or x direction. However, each of the small cubes within this bar still will expand according to the laws of the temperature and expansion. Therefore, all the expansion will be in the y and z directions because it will be unable to expand in the x direction. This means that the bar will become slightly larger but not longer (Figure 23-5B). This is the principle of upsetting or deformation. Molecules have rearranged themselves and have expanded in two directions, but not in the third direction. Now we will allow the bar to cool down to room temperature. The small cubes within the bar will tend to contract in the x, y, and z directions and will contract the same amount that they expanded. This means that after cooling back to room temperature the bar will be slightly shorter than it was originally (Figure 23-5C). It will be slightly larger from the upsetting force that occurred during the heating cycle. This illustrates the effect of restraint and shows that the heated portion will not return to its original shape. This illustration, however, may be too elementary, at least when we are considering differential heating with respect to welding. To be a little more practical, we assume the same round rod between two immovable surfaces but in this case will include a compression spring (Figure 23-6A). We will now go through the same heating cycle. We will heat the rod the same 1000 °F (538 °C), but in this situation it will expand in length (x direction) as well as in the y and z directions; however, there is a degree of restraint in the length or x direction. The rod does actually become longer and will cause the spring to compress slightly. Therefore, because of the restraint, by the spring, the bar length increase will be less than if it were completely unrestrained. The spring exerts force against the rod, which restrains the rod from expanding as much as when free. There will be expansion in the x and y and z directions so that the bar will actually become somewhat larger as well as longer (Figure 23-6B). When the heat is removed and the part comes back to its original room temperature it will be somewhat shorter than originally and somewhat larger in diameter (Figure 23-6C). In other words, the deformation will not be quite so great because the restraint was not so great. This is more similar to what actually happens to weld metal in a differentially heated and cooled cycle.

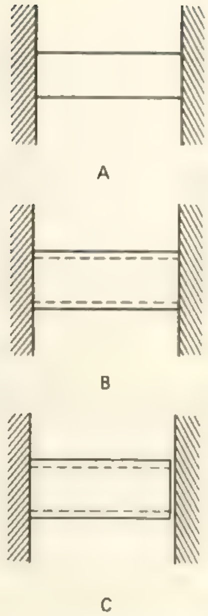


FIGURE 23-5 Round rod in vice.

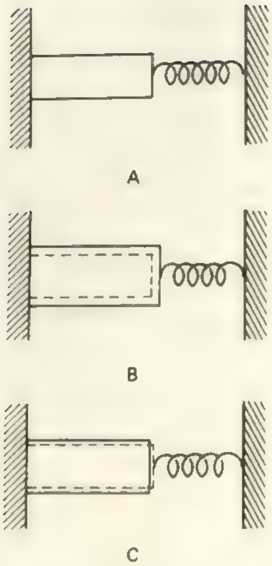


FIGURE 23-6 Round rod in vice with spring.

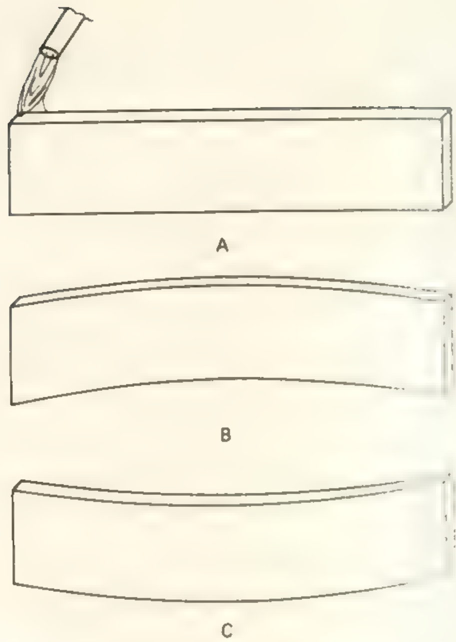
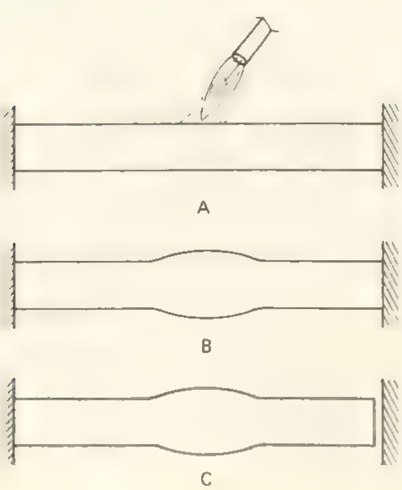


FIGURE 23-8 Long rectangular bar heated on one edge.

Another example should be given to illustrate this. Again use a round rod, but in this case considerably longer, and again place it between the immovable surfaces (Figure 23-7A). In this situation, however, we will heat only the center portion of the rod. In the heated area, the temperature rise will cause expansion in all three directions. Restraint will be exercised by jaws and the compressibility of unheated metal; but, this is relatively small. In the heated area there will be expansion in the *y* and *z* directions so that the diameter of the bar in the heated area will become larger (Figure 23-7B). This is a perfect example of plastic deformation or of upsetting. When the bar is allowed to cool contraction will occur uniformly in the *x, y,* and *z* directions and, in effect, the length of the bar will be slightly reduced when it returns to room temperature (Figure 23-7C).

FIGURE 23-7 Long rod in vice.



One final example should be discussed to bring the problem of differential heating and upsetting into focus with regard to practical applications. This is illustrated by the use of a piece of flat rectangular bar stock fairly thin and fairly wide; use ¼ in. (6.4 mm) thick, 2 in. (50 mm) wide, and 12 in. (300 mm) long. Pass a high-temperature heat source such as a gas tungsten arc torch along one edge (Figure 23-8A). This creates differential heating across the width of the bar. The top edge of the bar will be heated to the molten stage. Approximately ½ in. (13 mm) below the edge in the bar it will remain at room temperature. At the bottom edge of the bar it will also be at room temperature. Each small increment of metal in the upper edge of the bar is being heated to approximately 2000 °F (1093 °C) and it will expand in all three directions. Slightly below the top edge, the bar will be heated to a smaller degree or to a lower temperature; however, even at this point there will be a degree of expansion in all three directions. Farther down with little or no change of temperature there will be little or no change in dimension. This will cause the top edge of the bar to tend to expand (Figure 23-8B), but it is intimately a part of the lower portion of the bar, which has no tendency to expand because it is not heated. The restraint is therefore from the lower portion of the bar, which will restrain the upper portion from expanding to the amount to which it would expand if it were free of the remaining portion of the bar. Plastic deformation will occur and the bar will become slightly thicker at the heated edge. When the bar cools contraction will occur in all three directions and this will cause the upper edge of the bar to shorten. Shortening the upper edge of the bar without

shortening the center or lower edge of the bar will cause warpage, (Figure 23-8C). Shortening one edge of a bar and not shortening the other edge will in effect create a curved bar.

There is another factor that must be considered. This is the fact that metals have lower strengths at high temperatures. In other words, as the temperature of a metal increases, its strength decreases. This can be shown by a plot curve on which we plot the yield strength of the metal against temperature. In the case of steel, which might have a yield strength of approximately 36,000 psi, (25.3 kg/mm^2), we have a curve shown in Figure 23-9. As the temperature rises the strength decreases at approximately somewhere between 1000°F (538°C) and 1500°F (816°C) depending on its composition. For low-carbon mild steel when the temperature is above 1500°F (816°C) the strength is reduced drastically. This factor is involved because in welding operations a portion of the base metal goes above this temperature since surface melting is involved.

One other factor must be considered with regard to the temperature differential in different parts of a metal structure. In the case of the rectangular bar in the previous example, the bar was made of steel. When the temperature at the top edge was practically at the molten stage, a quarter of the way down it would be at a relatively low temperature, and halfway down the width of the bar and at the bottom edge, it would be at room temperature. If the bar is copper or aluminum, another factor becomes important: that of *thermal conductivity*, which has been previously defined. The property of conductivity is shown in Figure 15-1 for the more common metals. The thermal conductivity of copper is the highest, that of aluminum is approximately half this figure, but that of steels is only about one-fifth as much. If the bar were made of copper instead of steel, the temperature at the top would be practically at the molten stage but the heat would quickly move within the bar to the lower portions so that the temperature differential would not be nearly so great. This would also be true of aluminum and other high-thermal-conductivity metals. This is important in discussions of warpage since the higher the thermal conductivity the less effect differential heating will have. This physical property should be considered, along with the fact that arc temperatures are very similar but the metal melting points are somewhat different.

When welds are made we must take into consideration all the factors mentioned above and try to determine how each one reacts alone but also how they react with one another. To understand these relationships better, consider a weld bead made longitudinally on a relatively thin rectangular plate (Figure 23-10). When making a weld bead on the plate the deposited weld metal is momentarily at a temperature of about 3000°F (1649°C), slightly above its melting point. The base metal immediately under the weld bead is also brought to the molten stage. As the weld metal cools and fuses to the base metal immediately under it, it takes shape and forms a bead. The cooling solidification pattern is such that the molten base metal will cool and freeze first. The lower portion of the weld bead then freezes and finally the total, including the upper portion of the weld bead, freezes. At the point of solidification the molten metal has little or no strength. As it cools it acquires strength (Figure 23-9). At this time it is also in its expanded form because of its high temperature. Additionally, the weld metal is now intimately fused to the base metal and they work together, not independently. As the metal continues to cool it acquires higher strength and is now contracting in all three of the x, y, and the z directions. These factors are further complicated because the arc depositing molten metal is a moving source of heat. In addition, the cooling dif-

FIGURE 23-9 Temperature–yield strength relationship.

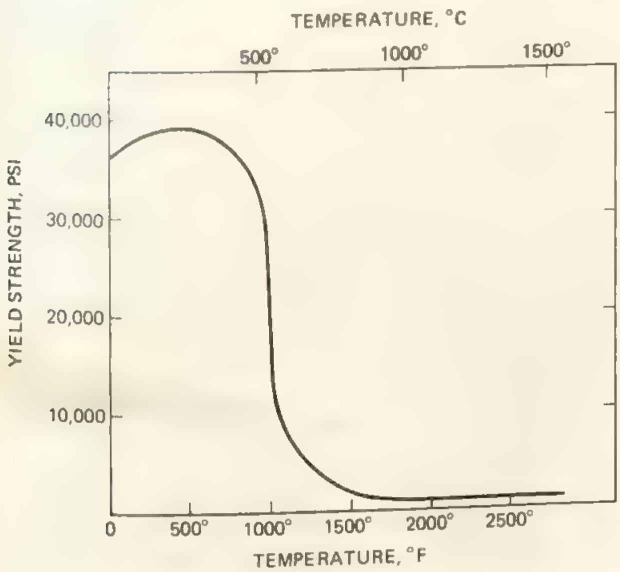
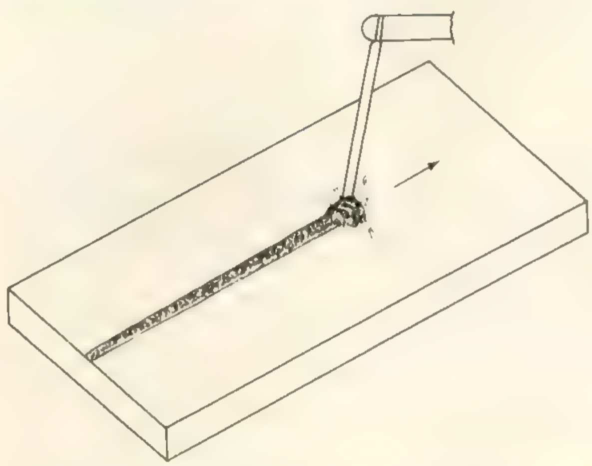


FIGURE 23-10 Bead on plate.

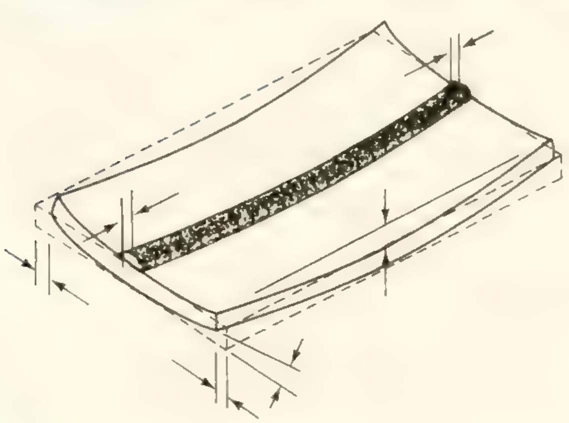


ferential is also a moving factor, but does tend to follow the travel of the arc. With the temperature further reducing and each small increment of heated metal tending to contract, contracting stresses will occur and there will be movement in the metal adjacent to the weld. The unheated metal tends to resist the cooling dimension changes of the previously molten metal. Temperature differential has an effect on this. If it is a low-conductivity metal, the changes will occur over a relatively small distance. If the metal has high thermal conductivity, the heating differential will be less and the change in dimensions will be spread over a larger area. In this bead-on-plate example, the cooling shrinkage changes are above the centerline of the thickness of the plate. The tendency of the weld bead to shorten in length, in thickness, and in width tends to warp the plate by shortening the weld area and shortening the top surface in both directions. An exaggeration of how a plate of this type will warp is shown in Figure 23-11.

Running a weld bead on the edge of a bar would be similar to the example of a heat source on the edge of the bar. The effect might be slightly more since additional molten or high-temperature metal is deposited on the edge of the bar. The deposited metal becomes integral with the bar and provides a greater mass of metal solidifying, gaining strength and cooling. This shortening of the heated edge without a similar change in the nonheated edge would create the warpage which would be the same or similar to that shown in Figure 23-8.

When making a weld joint, specifically a butt joint, between two narrow and relatively thin plates, another factor becomes important. This factor has to do with heat input or the speed of welding or travel. Refer to Figure 23-12, which shows the weld joint partially made. If the same joint is welded with covered electrodes the unwelded end of the joint tends to close or the parts become closer together. If the same joint is welded with submerged arc, the unwelded end of the joint tends to open or the parts become farther apart. The explanation is complicated since it involves the geometry of the pieces being joined, the thermal coefficient of expansion, the thermal conductivity, the mass of molten metal, but most importantly, the travel speed of the heat source or arc. If the travel speed is relatively fast, the effect of the heat of the arc will cause expansion of the edges of the plates and they will bow outward and open up the joint. If the travel speed is relatively slow, the effect of the arc temperature and the cooling down will cause contraction of the edges of the plates and they will bow inward and close up the joint. This is the same as running a bead on the edge of the plate. In either case it is a momentary situation which continues to change as the weld progresses. By experimenting with current and travel speed, the exact speed can be found for a specific joint design so that the root will neither open up or close together. This is one of the advantages of fine wire gas metal arc welding of sheet metal. The heat input balance, using normal procedures, approaches this travel speed relationship and for this reason warpage is minimized. Conversely when using the gas tungsten arc process on sheet metal the travel speed is inherently slower and greater warpage usually results.

FIGURE 23-11 Warpage produced by bead on plate.



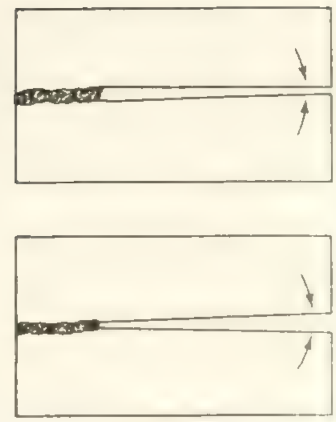


FIGURE 23-12 Butt joint showing warpage

All these factors must be considered, yet they are not the entire story for more complicated type welds. For example, in a fairly large fillet weld we have all the factors mentioned previously, plus more. Consider a single-pass fillet weld used to make a corner joint with the fillet weld on the inside (Figure 23-13). A fillet weld, by definition, has a triangular cross section. In making the weld, the base metal immediately under the fillet in the horizontal plate and the vertical plate are molten. The fillet itself is completely molten and soon after it is deposited it begins to cool and to freeze. Initially it has little strength, but the strength rapidly increases as the temperature decreases. From the geometry of the joint we have absolute restraint where the edge of the vertical plate is in contact with the surface of the horizontal plate. The metal deposited is now integral with the material of the two parts being joined and as it cools its strength is increas-

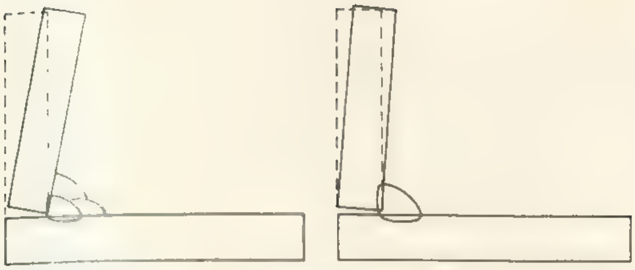


FIGURE 23-13 Inside fillet corner joint.

ing but it is also decreasing in volume. Each and every small increment of the heated metal is decreasing in volume in its x, y, and z directions. As each increment shrinks and as the surfaces between the two plates are restrained and cannot shrink, we see the evidence of warpage. Normally, the fillet weld freezes from the root to the face and the strength would increase in the cooling metal in this same relationship. However, one reason why fillet welds are a special case is the fact that at the root of the fillet there are less small increments of metal that are contracting. But as we progress toward the face of the fillet, there are more and more increments that are contracting. Therefore, there is more shrinkage or actual movement at the face of the fillet than there is at the root of the fillet, not only because of the larger volume of metal at the face but also because of the restraint between the plates at their interface. If the plates had not been tightly placed together, there would be less total angular warpage at the joint. The fillet weld is particularly vulnerable to warpage because of these two factors. Figure 23-13 shows how this warpage occurs. Note that all the warpage occurs on one side of the centerline of the vertical plate and on the top side of the centerline of the horizontal plate.

One practical method of eliminating the angular distortion produced by a single-fillet weld is to utilize the T-type joint or the corner joint with the one plate inset so that double-fillet welds would be made. If the fillet welds could be made on both sides simultaneously it would greatly reduce the angular warpage since the two would be working against each other and their shrinkage stresses and their shrinkage dimensions would balance out. However, the longitudinal shrinkage will still occur and in this case we will have highly stressed welds that might be stressed to the yield point of the weld metal at least at the initial freezing period.

If one fillet is made and then the second fillet is made, there will be a certain amount of angular distortion because the initial fillet will freeze first and create some distortion. However, if the second fillet is made larger than the first fillet, this can be somewhat overcome. In common practice it is normal to place one pass of the fillet on one side then to place two passes of the second fillet on the other side and finish up on the first side with its second pass. This type of procedure tends to reduce angular warpage of fillet welded T joints.

The cross-section geometry of other welds and the technique of making such welds also contribute to the warpage problem. Consider a weld joint that utilizes a single V weld. A single V weld in thinner material can be made with one pass. Figure 23-14 shows a single-pass V-groove butt joint and the warpage that would occur. As the weld is deposited in the groove the adjacent base metal is raised to its melting temperature and becomes molten. The entire weld is molten but immediately begins to cool and freeze. As it freezes it increases its strength, but it still has considerable temperature, on the order of 1000°F (538°C). At the bottom of the root of the V groove, each increment of weld metal shrinks in all three directions. At the center of the weld each increment of metal shrinks in all three dimensions, and at the face of the weld the same is true. A weld in thinner material may freeze throughout its cross section almost simultaneously. Since there is more volume of metal freezing and contracting at the top or wide portion of the joint, there will be more total dimensional contraction at this point. The bottom of the joint will contract a small amount. Angular distortion will occur because of the greater amount of weld metal at the top of the joint.

FIGURE 23-14 Single-pass single-V-groove butt joint.

A change in weld joint design has an effect on warpage. If the root opening is increased and the bevel angle is reduced, the difference in the amount of weld metal at the root of the weld and at the face of the weld would be more similar and therefore angular distortion would be less. This is one reason for reducing the groove angles to change the ratio of the metal at the root and at the face. Another approach at reducing angular distortion is to use the double V preparation, in which one portion of the weld would be made on one side of the plate and the other portion on the other side. This is applicable only to thicker plates, where it can be justified to have the double preparation. On a thinner material the square groove weld has an advantage since the shrinkage dimension at the root of the weld would be the same as that at the face of the weld. The differential in the cooling rate might create some change which would lead to some angular distortion. In all these cases, however, the longitudinal distortion or shrinkage will still occur and create the shortening of the total weld and its effect on distortion.

One of the interesting results of electroslag welds is the fact that they produce little or no angular distortion. Normally in the electroslag welding process, square groove preparation is used. This means that the root and

FIGURE 23-15 Multiple-pass single-V-groove butt joint.

face of the weld has the same dimensions. The weld is made in one pass; thus the root and the face are made simultaneously. As the electroslag weld cools there is some distortion from the start of the weld to the finish of the weld, but this is relatively small. The angular distortion which would tend to warp plates out of line is nonexistent. This is attributed to the fact that the incremental portions of weld metal solidifying and contracting are the same at the root and the face of the weld, and thus we have equal contraction, which eliminates the angular distortion.

Another type of weld that has almost square sides is the electron beam weld with its high depth-to-width ratio. The cross section of an EB weld is almost rectangular, since the width at the face and the width close to the root are almost the same. Angular distortion for electron beam welds is also very small since the sides of the weld are nearly parallel.

The problem of distortion in fillet welds and in V-groove welds increases as the size of the welds increase. The groove weld shown in Figure 23-15 will require many passes to complete the joint or fill the groove. In most processes the number of passes depends on the technique, the size of the electrode, the welding current, etc. With shielded metal arc welding the first or root pass would be placed in the joint and in effect would create a homogeneous structure between the two parts being joined. Very little angular distortion would result from the root pass weld. The next pass would cause some angular distortion. In the second pass the first pass acts as a restraining force, assuming that it is not completely melted by the second pass as it is deposited. The freezing of the second pass would create shrinkage of the deposited metal but the root pass would offer restraint and there would be shrinkage closer to the upper surface of the plates and less at the bottom surface. When the next pass is made there would be more restraint at the root of the joint and more shrinkage at the surface of the weld. Successive passes are larger and wider and there is a greater mass of weld metal cooling and shrinking. This condition continues until the joint is completed. Each new pass creates its heating and cooling and shrinking cycle with previous passes acting as restraint. In effect, it is like a hinge with the root, of the first pass, acting as the hinge pin, and each additional pass tending to bring the edges of the joint closer together. For this reason multipass single-V-groove welds are particularly susceptible to angular distortion.

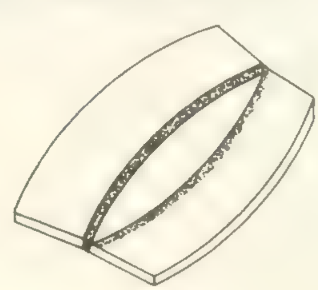
It has been proven by many tests and experiments that the larger number of passes used increases the angular distortion in single-groove welds. This disproves the theory that by making many small passes with low currents the distortion will be reduced. This is not true because each pass produces molten metal and in each pass the weld metal cools and shrinks. The mass of molten metal and the mass of metal restraining the shrinkage does affect the relationship, however. The additional applications of heat make for more angular distortion of multipass single fillets and multipass single-V-groove welds. A solution to this is the use of larger passes, larger electrodes, or processes that provide larger passes.

The obvious solution to such situations is to go to the double- weld, the double-V, or double-bevel preparation for thicker materials. The double fillet should be used if at all possible, and if not, a combination of fillet and groove welds. The principle of using double welds is to equalize the shrinkage on both sides of the centerline of the weld joint. If one side of the centerline contracts more than the other, it will create angular distortion.

Angular distortion is greatly reduced by balancing the welding on either side of the centerline of the joints being made. The distortion that occurs in the joint is based on the shrinkage which follows thermal cooling versus restraint conditions previously described. Even though there may be no visible evidence of warpage there are probably high stresses approaching yield points of the metals in and near the joint. If a square groove butt weld were made between two edges of two flat plates and if the welds were made from both sides properly, there would be little evidence of warpage. However, if we would saw through the throat of the weld its entire length the warpage would become immediately evident. The result would be the same as two bars with welds on one edge, as described previously (Figure 23-16).

The principle of balanced welding must be considered in designing and controlling warpage of weldments. In the case of the bar stock just mentioned, the centerline of the bar is actually its neutral axis. The neutral axis is the geographical center of gravity of the cross section of the part. Weldments also have a center of gravity or neutral axis which can be calculated based on the thickness and size of the component parts. An example of a symmetrical cross-sectional part is a fabricated

FIGURE 23-16 Square groove butt weld cut apart.



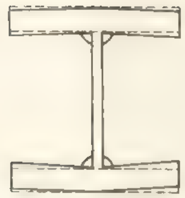


FIGURE 23-17 Fabricated beam.

wide-flange or H-type beam (Figure 23-17). To build such a beam will require the welding of two flange plates to a web plate. If the parts are all equal size and thickness, the center of gravity would be the exact center of this assembly. The welds to join the flanges to the web would be equally spaced about the center of gravity. If all four of these fillet welds could be made simultaneously it would be possible to produce the beam without longitudinal distortion. The edges of the flanges will pull in slightly, because of the angular distortion produced by each fillet weld. If the welding can be balanced around the neutral axis of the weldment, the distortion can be greatly reduced. This is the principle of balanced welding. If each application of heat is done in a logical manner about the center of gravity of the weldment, it tends to keep the weldment to true shape. A box section, such as a box column, presents the same type of opportunity. The weldment is symmetrical around its neutral axis and the applications of the welds are also symmetrical. If all four welds could be made simultaneously a straight part would result. In practice it is rarely possible to make all four welds simultaneously. Some of these types of structures have been welded in the vertical position to make the welds simultaneously. A more common practice, however, is to make two of the welds at one time and then make the remaining two welds. Sometimes it is possible to vary the sizes of the welds to produce balanced stresses to create a straight member. Unfortunately, most weldments are not symmetrical around their neutral axis, and more often than not most welding has to be done on one side or another of the neutral axis, and this creates the warpage.

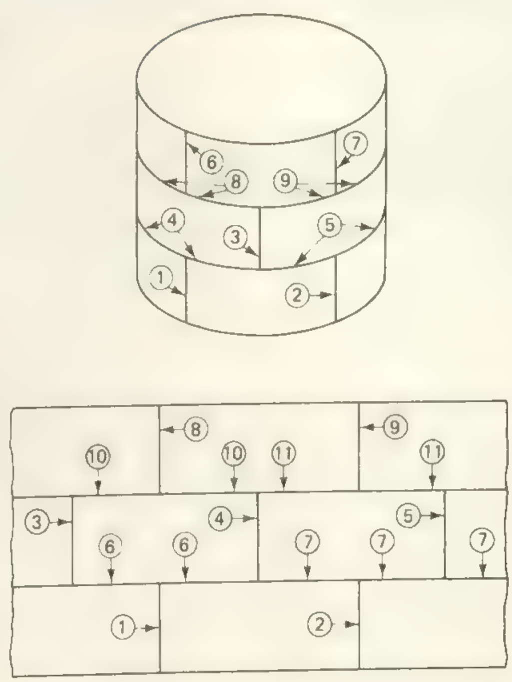
The following factors should be taken into consideration in order to reduce welding warpage.

1. The location of the neutral axis and its relationship in both directions
2. The locations of welds, size of welds, and distance from the neutral axis in both directions
3. The time factor of welding and cooling rates when making the various welds
4. The opportunity for balancing welding around the neutral axis
5. Repetitive identical structures and varying the welding technique based on measurable warpage
6. The use of procedures and sequences to minimize weldment distortion

It is impossible to provide more than general guidelines in warpage control. It is not a true science and even when identical parts are made with identical procedures the warpage of each assembly will be different. This can result from stresses within parts themselves prior to welding or seemingly insignificant changes in technique by different welders. However, based on certain rules it is possible to minimize distortion on most weldments. For example, when making the welds on a large box structure such as a ship hull, the sequence of welding can be varied from side to side and from top to bottom to minimize distortion. At shipyards exact measuring devices are used to determine the amount of distortion produced by welding. Corrective action is taken to maintain straightness of the structure. This same technique can be used for any large engineering structures. If the structure tends to warp to one side welding can be increased on the other side to compensate and by measuring continuously and altering procedures the structure can be made to come true. On large weldments it is important to establish a procedure to minimize warpage. The order of joining plates in a deck or on a tank will affect stresses and distortion. As a general rule transverse welds should be made before longitudinal welds. Figure 23-18 shows the order in which the joints should be welded.

Platens and bases that are large and thin and usually made of "egg crate" design can also be regulated by making certain joints first, particularly the joints joining the

FIGURE 23-18 Order of making weld joints.



web sections together prior to joining them to the top and bottom or flange sections. The joining of the web sections to the flanges should be regulated and constant measurements made to determine that the weldment remains true.

The design and type of weldment have much to do with the warpage that is encountered. Large weldments made of relatively thin materials have a tendency to warp. Control is possible with proper procedures. Large weldments made of extremely heavy or thick members have a greater degree of restraint and the amount of warpage may be less. Balancing the welding and monitoring the effect of changes in technique and procedure are the best ways of controlling warpage in large structures.

Warpage can be minimized in smaller structures by different techniques. These include:

1. The use of restraining fixtures, strong backs, or many tack welds
2. The use of heat sinks or the fast cooling of welds
3. The predistortion or prebending of parts prior to welding
4. Balancing welds about the weldment neutral axis or using wandering sequences or back-step welding
5. Intermittent welding to reduce the volume of weld metal
6. Proper joint design selection and minimum size
7. As a last resort, use preheat or peening

Each of these techniques has advantages and can be used in certain applications. No one of them is a cure-all for the problem of weld warpage. Fixtures can be very effective, but fixtures must be extremely strong if they are to resist warpage. Many fixtures are not sufficiently strong for this purpose and, even with fixtures, balanced welding is necessary. Strong backs or face plates can be used to physically restrain the parts. Massive tack welds and heavy bracing can also be used. If the weldment is stress relieved with bracing in place, warpage will be minimized. Figure 23-19 shows a dipper for a large power shovel with massive bracing. Each half was stress relieved separately, because of furnace size limitations, with the bracing in place. Distortion was minimized.

Prebending or predistortion of parts or providing special dimensions for warpage or prewarping with the hope the the welds will bring the parts into proper alignment, can be helpful. This type of technique is most useful when repetitive products are being welded and a history of the amount of warpage involved can be determined. This technique is particularly useful in field erection of large structures. It is also used for welding premachined parts together to avoid finish machining of a total weldment.

Rapid cooling by means of heat extractors or heat sinks has been used successfully in the aircraft industry. By means of hydraulic or pneumatic clamps the parts of the weldment are put in intimate contact with large masses of highly conductive metal. These are known as heat

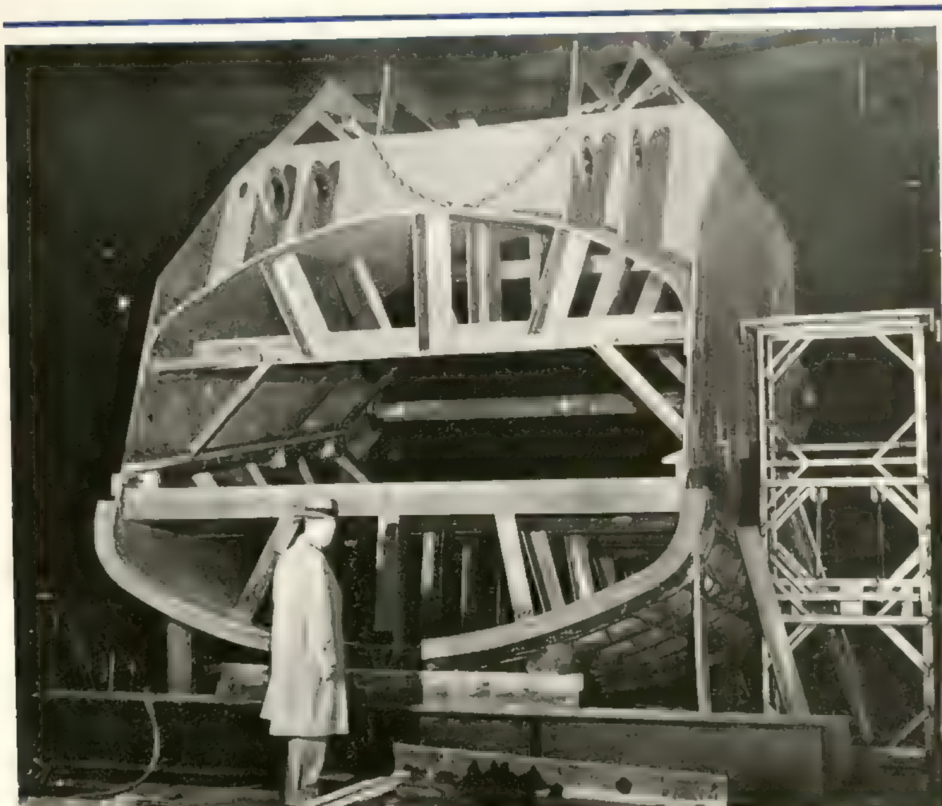
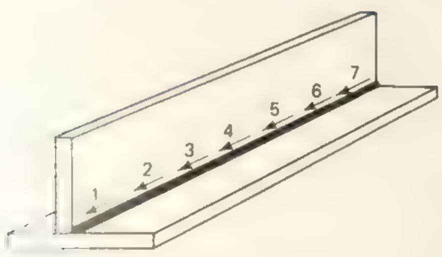


FIGURE 23-19 Heavy braces in weldment.

sinks, which pull the heat away from the weld quicker than normal. This creates a more uniform heat distribution and reduces the heat differential and distortion. Some weld fixtures have water-cooled heat sinks to help reduce distortion.

The use of different types of techniques, such as the back-step technique shown in Figure 23-20, has an advantage in that each small increment will have its own shrinkage pattern which then becomes insignificant to the total pattern of the total weldment. This technique may be rather time consuming and questionable for certain types of applications.

FIGURE 23-20 Back step technique.



The use of intermittent welding can be helpful; however, intermittent welding is merely a method of reducing the amount of weld metal in certain areas to avoid warpage at that specific area. Using the smallest possible weld size helps reduce distortion.

As a last resort use peening. Peening actually works the weld metal and expands it which counteracts the shrinkage that occurred upon cooling. Peening is hard to regulate, it is noisy, and usually not the best solution. If the weldment is warped so that it cannot be used it may be salvageable by mechanical or thermal methods. Mechanical methods involve the use of force such as a straightening press, jacks, clamps, and so on. This can be expensive but justifiable. Thermal methods involve local heating to relieve stresses in some cases or to cause corrective warpage. Heat is usually applied by torches. Caution should be exercised to not overheat the metal, especially heat-treated materials. Local torch heating should not be used on highly thermal conductive metals such as aluminum or copper. The heat will be conducted away so quickly that local upsetting will not occur. This was covered in a previous section.

Finally, one of the best approaches to weldment distortion is the intelligent design of the weldment itself. With intelligent review it is possible to design or redesign a weldment to better place the welds in a balanced geometry around the neutral axis of the weldment. Many times this can change the location of a weld. It might involve the use of a bend, it might involve the use of two welds, but if it can be accomplished it will greatly enhance the distortion control of the weldment.

23-3 WELD STRESSES AND CRACKING

The subjects of weld stresses, cracking, weld distortion, lamellar tearing, brittle fracture, fatigue cracking, weld design, and weld defects are so interrelated that it is almost impossible to treat them separately. All of these factors relate to weldment failure and it is weldment failure that should be eliminated. For clarification and ease of understanding, these factors are segregated and discussed in an orderly fashion. Weld distortion and warpage, which are greatly related to weld stresses, were treated in Section 23-2. In this section the problem of welding stress and its effect on weld cracking is explained. The next section will cover brittle fracture, lamellar tearing, and fatigue cracking, which are more or less service oriented.

Residual Stresses

It was just pointed out in Section 23-2 that metals expand and contract the same amount when heated and cooled the same amount, if the metal is in no way restrained. It was also explained that the heating and cooling that occur in welding are not uniform and there is a temperature difference between the area at the weld and areas adjacent to the weld which in effect creates a restraint on the higher temperature heated metal. The amount of nonuniform heating and the partial, and in some cases almost total, restraint creates stresses within the metal in the weld area and including the weld metal. It was also brought out that as metal is heated to a higher temperature its strength is greatly reduced; however, as the metal cools it regains its strength up to the yield point. If further temperature change occurs the stresses will be greater than the yield point of the metal; however, yielding will occur so that the retained or residual stress will be at the yield point of the metal involved. It was further explained that heated metal expands in all three directions: the x, y, and z directions. Also that as metal cools it contracts in the same three directions but that restraint is always involved. This means that yield point stresses within the weldment may occur in all three directions simultaneously. These internal or remaining stresses are known as residual stress, the "stress remaining in a structure or member as a result of thermal or mechanical treatment or both."

When stresses applied to a member exceed the yield strength the member will yield in a plastic fashion so that the stresses will be reduced to yield point. This is normal in simple structures with stresses occurring in one direction on parts made of ductile materials. Shrinkage stresses due to normal heating and cooling do occur in all three dimensions, however. For example, in a thin flat plate there will be tension stresses at right angles, in other words, in the x and y directions. As the plate becomes

thicker or in extremely thick materials the stresses occur in the x, y, and z—or through—directions as well.

When simple stresses are imposed on a thin brittle material, the material will fail in tension in a brittle manner, the fracture will exhibit little or no ductility. In such cases there is no yield point for the material since the yield strength and the ultimate strength are practically the same. The failures that occur without plastic deformation are known as brittle failures. When two or more stresses occur in a ductile material and particularly when three stresses occur in the x, y, and z directions in a thick material, brittle fracture may occur which is similar to the fracture of a brittle material.

Residual stresses are not peculiar to weldments. They also occur in other types of metal structures, such as castings and forgings, and even hot rolled shapes. Several examples of spontaneous fracturing of rolled structural shapes under conditions of zero external load have been reported.(2) In one case an I beam fractured spontaneously under a condition of zero external load when the beam was lying flat on the ground and under normal temperature conditions. The failure occurred through the center of the web splitting the beam its entire length. High residual stresses also occur in castings and forgings as a result of the differential cooling that occurs. The outer portion of the part cools first and the thicker and the inner portion considerably later. As the parts cool, they contract and pick up strength in accordance with the strength temperature relationship, so that the earlier portions that cool go into a compressive load and the latter portions that cool go into a tensile stress mode. In complicated parts the stresses may cause warpage.

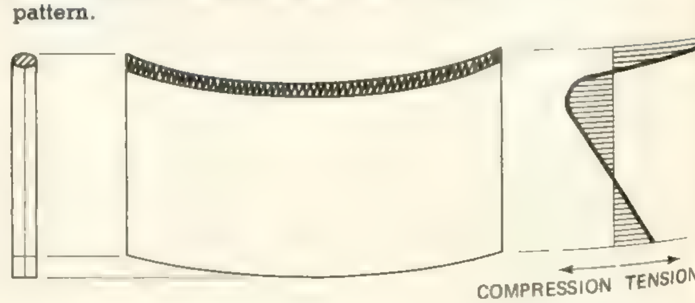
Residual stresses must not always be considered as detrimental. They may have no effect or may have a beneficial effect on the service life of parts. Normally, the outer fibers of a part are subjected to tensile loading and thus with residual compression loading there is a tendency to neutralize the stress in the outer fibers of the part. An example of the use of residual stress is in the shrink fit assembly of parts. A typical example is the cooling of sleeve bearings to insert them into machined holes, then allow them to expand to their normal dimension to retain them in the proper location. Sleeve bearings are used for heavy slow machinery and are subjected to compressive residual loading, keeping them within the hole. Also, on the subject of bearings, large roller bearings are usually assembled to shafts by heating them to expand them slightly so that they will fit on the shaft, then allowing them to cool, to produce a tight assembly. One of the most dramatic uses of shrink fit assembly for heavy-duty service is the shrink fitting of steel tires on wheels for railroad locomotives. In this case, the tire is made of relatively high-carbon steel with the required flange. These tires are heated to an elevated temperature and then placed on the locomotive wheel and allowed to cool. This differential heating and cooling allow the tire to shrink around the wheel and make a very strong contact or mechanical connection. Even with the tremendous loads encountered in use, the residual stresses continue to hold the tire on the wheel and thus there is no relaxing of the stresses resulting from mechanical working. It seems rather certain that normal operating loads cannot be expected to reduce the magnitude of internal residual stresses.

Many investigations have been made and techniques established to measure residual stresses. Residual stresses occur in all arc welds but it is only in the more simple joints that accurate measurements have been made. Probably the most common method of measuring has been to produce weld specimens and then to machine away specific amounts of metal which in effect are resisting the tensile stress in and adjacent to the weld and then to measure the movement that occurs. This can be done to produce data showing the magnitude of the residual stresses. Another method is the use of grid marks or data points on the surface of weldments that can be measured in multiple directions. Cuts are made to reduce or release residual stresses from certain parts of the weld joint and the measurements are taken again. The amount of movement relates to the magnitude of the stresses. Another technique is to utilize extremely small strain gauges and gradually mechanically cut the weldment from adjoining portions to determine the change in internal stresses. In this way, experts have been able to establish patterns and actually determine amounts of stress within parts that were caused by the thermal effect of welds.

Based on these data, it is possible to establish a pattern of residual stresses that occurs in a simple weld.

As an example of this, the residual stresses in an edge weld are shown in Figure 23-21. The metal close to the weld tends to expand in all directions when heated by the welding arc. This metal is restrained by adjacent cold metal and is slightly upset or its thickness slightly increased during this heating period. When the weld metal starts to cool the upset area attempts to contract but is again restrained by cooler metal. This results in the heated zone (upset zone) becoming stressed in tension. When the weld has cooled to room temperature the weld metal and the adjacent base metal are under tensile stresses close

FIGURE 23-21 Edge welded joint: residual stress pattern.



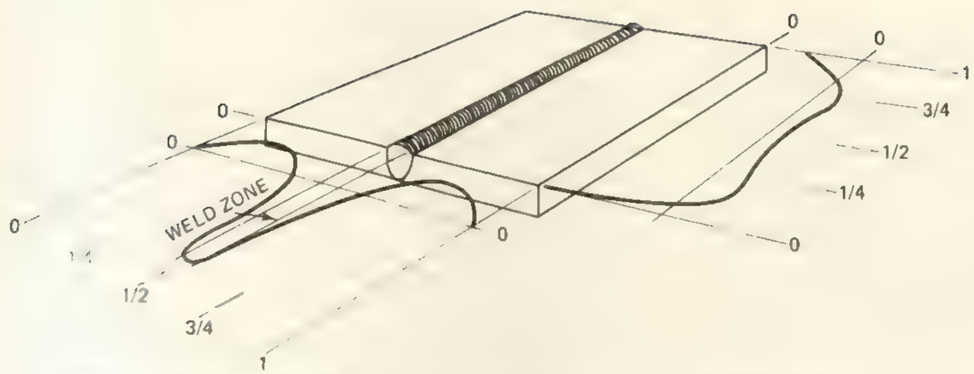


FIGURE 23-22 Butt welded joint: residual stress pattern.

to the yield strength. Therefore, there is a portion that is compressive and beyond this another tensile stress area. Thus the two edges are in tensile residual stress with the center in compressive residual stress, as shown by the figure.

The residual stresses in a butt weld joint made of relatively thin plate are more difficult to analyze. This is because stresses occur in the longitudinal direction of the weld and perpendicular to the axis of the weld. The residual stresses within the weld are tensile in the longitudinal direction of the weld and the magnitude is at the yield strength of the metal. The base metal adjacent to the weld is also at yield stress parallel to the weld and along most of the length of the weld. When moving away from the weld into the base metal the residual stresses rapidly fall to zero, and to maintain equilibrium, change to compression (Figure 23-22). The residual stresses in the weld at right angles to the axis of the weld are tensile at the center of the plate and are compressive at the ends. For thicker materials when the welds are made with multipasses, the relationship is different because of the many passages of the heat source. Except for single-pass simple joint designs the compressive and tensile residual stresses can only be estimated. In order to determine at least generally the mode and type of stresses it is important to remember that as each weld is made it will contract as it solidifies and gains strength as the metal cools. As it contracts it tends to pull, and this creates tensile stresses at and adjacent to the weld. Farther from the weld or bead the metal must remain in equilibrium and therefore compressive stresses occur. In heavier weldments when restraint is involved, movement is not possible and therefore residual stresses are of a higher magnitude. For example, in a multipass single-groove weld the first weld or root pass originally created a tensile stress. The second, third, and fourth passes contract and cause a compressive load in the root pass. As more passes are made until the weld is finished the top passes will be in tensile load, the center of the plate in compression, and the root pass will have tensile residual stress again.

Residual stresses can be decreased in several ways. If the weld is stressed by a load to beyond its yield strength, plastic deformation will occur and the stresses will be made more uniform but still at the yield point of the metal. This will not eliminate residual stresses but at least will create a more uniform stress pattern. Another way to reduce high or peak residual stresses is by means of loading or stretching the weld by heating adjacent areas causing them to expand. The heat reduces the yield strength of the weld metal and the expansion will tend to reduce peak residual stresses within the weld. This technique will also make the stress pattern at the weld area more uniform. The more positive way of reducing high residual stresses is by means of the stress relief heat treatment. Here the weldment is uniformly heated to an elevated temperature at which the yield strength of the metal is greatly reduced. The weldment is then allowed to cool slowly and uniformly so that the temperature differential between parts is minor and thus the cooling will be uniform and a uniform low stress pattern will develop within the weldment. High-temperature preheating will also reduce residual stresses since the entire weldment is at a relatively high temperature and will cool more or less uniformly from that temperature and thus reduce peak residual stresses.

Weld Cracking

Residual stresses do contribute to weld cracking. Often, weld cracking will occur during the manufacturing operation of the weldment or shortly after the weldment is completed. Cracking may occur for many reasons and may occur years after the weldment is completed. It is our purpose to describe weld cracking that is a result of the residual stresses and weld cracking that occurs during the manufacturing operation or shortly thereafter.

Cracks are the most serious of the defects that occur in welds or weld joints in the weldments. Cracks are not permitted in most weldments, particularly those subjected to low-temperature service, impact loading, reversing stresses, or when the failure of the weldment will endanger life. It is therefore important to understand the mechanism of weld cracking so as to avoid weld cracks in all welds and weldments. Weld cracking that occurs

during or shortly after the fabrication of the weldment can be classified as hot cracking or cold cracking. In addition, welds may crack in the weld metal or in the base metal adjacent to the weld metal, usually in the heat-affected zone. Welds crack for a variety of reasons; such as:

- Insufficient weld metal cross section to sustain the loads involved
- Insufficient ductility of weld metal to yield under stresses involved
- Under-bead cracking due to hydrogen pick up in a hardenable type of base material

Restraint and residual stresses are among the main reasons for weld cracking during the fabrication of a weldment. Weld restraint can come from several factors. One of the most important is the stiffness or rigidity of the weldment itself. For example, if the weldment is made of thick material and it is of a highly restrained nature, there will be little chance for yielding or movement in the weld joint. If the weld metal does not have sufficient ductility, cracking will occur. Weld metal shrinks as it cools and if the parts being welded cannot move with respect to one another, and if the weld metal has insufficient ductility, a crack will result. Additionally, movement of welds may impose high loads on other welds and cause them to crack during fabrication. In such cases, the best solution is to use a more ductile filler material or to make the weld with sufficient cross-sectional area so that as it cools it will have sufficient strength to withstand cracking tendencies. The typical weld crack can occur in the root pass when the parts are unable to move.

Another factor involved is the rapid cooling of the weld deposit. If the base metal being joined is cold and the weld is relatively small it will cool extremely rapidly. Shrinkage will occur quickly and cracking can occur. If the parts being joined are preheated even slightly, the cooling rate will be lower and cracking can be eliminated. One of the advantages of preheat is to reduce the cooling rate of the weld and of the adjacent material. In addition, if the base metal is at an elevated temperature, it will have lower yield strength and will not be as restrictive as far as its restraint on the weld is concerned.

Another reason for this type of cracking can be the alloy or carbon content of the base material. When a weld is made with higher-carbon or high-alloy base material, a certain amount of the base material is melted and mixed with the electrode to produce the weld metal. The resulting weld metal has higher carbon and alloy content; it may have a higher strength but it has less ductility and as it shrinks it may not have sufficient ductility to cause plastic deformation and therefore cracking may occur. This can be eliminated by using a more ductile weld metal or by reducing the cooling rate of the weld and also by reducing the amount of base metal picked up and mixed in with the weld metal.

Another factor involved can be hydrogen pickup in the weld metal and in the heat-affected zone of the base metal. When using cellulose covered electrodes or when hydrogen is present because of damp gas, damp flux, hydrocarbon surface materials, and so on, the hydrogen in the arc atmosphere will be absorbed in the molten weld metal and in the adjacent high-temperature base metal. As the metal cools it will reject the hydrogen and if there is sufficient restraint cracking will occur. This type of cracking can be reduced by increasing preheat, reducing restraint, and, of course, eliminating the hydrogen from the arc atmosphere.

As a general rule, to eliminate weld cracking during fabrication it is wise to follow these principles:

- Use ductile weld metal.
- Avoid extremely high restraint or residual stresses.
- Revise welding procedures to reduce restraint.
- Utilize low-alloy and low-carbon materials.
- Reduce the cooling rate by use of preheat.
- Utilize low-hydrogen welding processes and filler metals.

When cracking is in the heat-affected zone or if cracking is delayed, the culprit is possibly hydrogen pickup in the weld metal and heat-affected zone of the base metal. Another important factor is the presence of higher-carbon materials or high alloy in the base metal. It is important to utilize low-hydrogen filler metals, to reduce cooling rates by means of preheat, and so on, and to use ductile filler materials.

One possible solution when welding high-alloy or high-carbon steels is to use the buttering technique. This involves surfacing the weld face of the joint with a weld metal that is much lower in carbon and alloy content than the base metal. The weld is then made between the deposited surfacing material and avoids the carbon and alloy pickup in the weld metal and thus allows a more ductile weld metal deposit. Care must be used, however, so that the total joint strength is sufficient to meet design requirements. Underbead cracking is greatly reduced by use of low-hydrogen type processes and filler metals. The use of preheat reduces the rate of cooling which tends to decrease the possibility of cracking. Reducing the cooling rate will materially reduce the chance of cracks. When welds are too small for the service intended, they will probably crack. This is common in tack welds where a small weld is expected to carry extreme loads which are impossible for the strength level of the tack welds. Many specifications list minimum size of fillet welds that can be used to join different thicknesses of steel sections. If these minimum sizes are used, cracking will be eliminated.

23-4 IN-SERVICE CRACKING

Our objective is always to design and build weldments that perform adequately in service. The risk of failure of a weldment is relatively small, but it can occur in structures such as bridges, pressure vessels, storage tanks, ships, penstocks, and so on. Welding has sometimes been blamed for the failure of large engineering structures, but it should be noted that failures have occured in riveted and bolted structures and in castings, forgings, hot rolled plate and shapes, as well as other types of construction. Failures of these types of structures occured before welding was widely used and still occur in unwelded structures today. Despite this, it is important from the welding point of view to make weldments and welded structures as safe against premature failure of any type as we possibly can. There are at least four specific types of failures that we should be aware of so that proper steps can be taken to avoid them. These types of failures are:

- ☐ Brittle fracture
- ☐ Fatigue fracture
- ☐ Lamellar tearing
- ☐ Stress corrosion cracking

Most of these problems have been mentioned in other sections of this book. In the design section, designers were alerted to the problems involved and how they can be avoided. In the quality control section, attention was focused on workmanship errors that might contribute to failures of these types. It is important to understand the background of these types of failure so that design, workmanship, and every other factor that might contribute can be considered and avoided. Each of these failure modes will be covered in detail.

Brittle Fracture

The fracture of metals is a very complex subject which is beyond the scope of this book; however, fracture can be classified into two general categories, *ductile* and *brittle*.

Ductile fracture occurs by deformation of the crystals and slip relative to each other. There is a definite stretching or yielding. There is a reduction of cross-sectional area at the fracture (Figure 23-23). Brittle fracture occurs by cleavage across individual crystals and the fracture exposes the granular structure; there is little or no stretching or yielding. There is no reduction of area at the fracture (Figure 23-24).

It is possible that a broken surface will display both ductile and brittle fracture over different areas of the surface. This means that the fracture which propagated across the section changed its mode of fracture. There are four factors that should be reviewed when analyzing a fractured surface: (1) growth marking, (2) fracture mode, (3) fracture surface texture and appearance, and (4) amount of yielding or plastic deformation at the fracture surface. Growth markings are one way to identify the type of failure. Fatigue failures are characterized by a fine texture surface with distinct markings produced by erratic growth of the crack as it progresses. The *chevron* or *herringbone* pattern occurs with brittle or impact failures. The apex of the chevron appearing on the fractured surface always points toward the origin of the fracture and is an indicator of the direction of crack propagation. The second factor is the fracture mode. Ductile fractures have a shear mode of crystalline failure. The surface texture is silky or fibrous in appearance. Ductile fractures often appear to have failed in shear as evidenced by all parts of the fracture surface assuming an angle of approximately 45° with respect to the axis of the load stress. Brittle or cleavage fractures have either a granular or a crystalline appearance. There is usually a point of origin of brittle fractures. The chevron pattern will help locate this point. The necking down of the surface of the fractured part is an indication of the amount of plastic deformation. There is little or no deformation for a brittle fracture and usually a considerably necked down area in the case of a ductile fracture.

FIGURE 23-23 Ductile fracture surface.

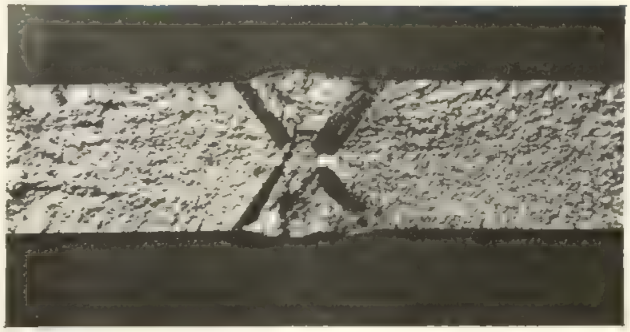


FIGURE 23-24 Brittle fracture surface.

One characteristic of brittle fracture is that the steel breaks quickly and without warning. The fractures propagate at very high speeds and the steels fracture at stresses below the yield strength normal for the steel. Mild steels, which show a normal degree of ductility, when tested in tension as a normal test bar, may fail in a brittle manner. In fact, mild steel may exhibit good toughness characteristics at room temperature. Brittle fracture is therefore more similar to the fracture of glass than fracture of normal ductile materials. A combination of conditions must be present simultaneously for brittle fracture to occur. This is reassuring since some of these factors can be eliminated and thus reduce the possibility of brittle fracture. The following conditions must be present: (1) low temperature, (2) a notch or defect, (3) a relatively high rate of loading, (4) triaxial stresses normally due to thickness or residual stresses, and (5) the microstructure of the metal.

Temperature is an important factor. However, temperature must be considered in conjunction with microstructure of the material and the presence of a notch. Impact testing of steels using a standard notched bar specimen at different temperatures shows a transition from a ductile type failure to a brittle type failure based on a lowered temperature. The change from ductile to brittle fracture is known as the transition temperature. Unfortunately, notched specimens are different from large engineered weldments. However, notched specimen results do provide a correlation that is useful in selecting the better material.

The notch that can result from faulty workmanship or from improper design produces an extremely high stress concentration which prohibits yielding in the normal sense. A crack, for example, will not carry stress across it and the load is transmitted to the end of the crack. It is concentrated at this point and little or no yielding will occur. Metal adjacent to the end of the crack which does not carry load will not undergo a reduction of area since it is not stressed. It is in effect a restraint which helps set up triaxial stresses at the base of the notch or the end of the crack. Stress levels much higher than normal occur at this point and contribute to starting the fracture.

The rate of loading is the time versus strain rate. The high rate of strain, which is a result of impact or shock loading, does not allow sufficient time for the normal slip process to occur. The material under load behaves elastically allowing a stress level beyond the normal yield point. When the rate of loading, from impact or shock stresses, occurs near a notch in heavy thick material, the material at the base of the notch is subjected very suddenly to very high stresses. The effect of this is often complete and rapid failure of a structure and is what makes brittle fracture so dangerous.

Triaxial stresses are more likely to occur in thicker material than in thin material. The z direction acts as a restraint at the base of the notch and for thicker material the degree of restraint in the through direction is higher. This is why brittle fracture is more likely to occur in thick plates or complex sections than in thinner materials. In addition, thicker plates usually have less mechanical working in their manufacture than thinner plates and are more susceptible to lower ductility in the z axis. The microstructure and chemistry of the material in the center of thicker plates have poorer properties than the thinner material which receives more mechanical working.

The microstructure of the material is of major importance with respect to the fracture behavior and transition temperature range. Microstructure of a steel depends on the chemical composition and production processes used in manufacturing it. A steel in the as-rolled condition will have a higher transition temperature or lower toughness than the same steel in a normalized condition. Normalizing, that is, heating to the proper temperature and slow cooling, produces a grain refinement which provides for higher toughness. Unfortunately, fabrication operations on steel such as hot and cold forming, punching, and flame cutting affect the original microstructure. This raises the transition temperature of the steel.

Unfortunately, welding tends to accentuate some of the undesirable characteristics that we wish to avoid in order to avoid brittle fracture. The thermal treatment resulting from welding will tend to reduce the toughness of the steel or possibly to raise its transition temperature in the heat-affected zone. The monolithic structure of a weldment means that more energy is locked up and there is the possibility of residual stresses which may be at yield point levels. Additionally, the monolithic structure causes stresses and strains to be transmitted throughout the entire weldment, and defects in weld joints can be the nucleus for the notch or crack that will cause fracture initiation. More information on brittle fracture is provided in Ref. 3.

The problem of brittle fracture can be greatly reduced in weldments by selecting steels that have sufficient toughness at the service temperatures. The transition temperature should be below the service temperature to which the weldment will be subjected. Heat treatment or normalizing or any method of reducing locked-up stresses will reduce the triaxial yield strength stresses within the weldment. Design notches must be eliminated and notches resulting from poor workmanship must not occur. This requires the elimination of internal cracks within the welds and of unfused root areas either by design or by accident. By closely following these conditions the possibility of brittle fracture will be eliminated or greatly reduced.

Fatigue Failure

Structures sometimes fail at calculated nominal stresses considerably below the tensile strength of the materials involved. The materials involved were ductile in the normal tensile tests but the failures generally exhibited little or no ductility. Most of these failures developed after the structure had been subjected to a large number of cycles of loading. This type of failure is called a fatigue failure. Fatigue failure is the formation of and development of a crack by repeated or fluctuating loading. When sudden failure occurs it is because the crack has propagated sufficiently to reduce the load-carrying capacity of the part. Fatigue cracks may exist in some weldments but they will not fail until the load-carrying area is sufficiently reduced. It is the repeated loading which causes progressive enlargement of the fatigue cracks through the material. The rate at which the fatigue crack propagates depends upon the type and intensity of stress and a number of other factors involving the design, the rate of loading, type of material, and so on.

The fracture surface of a fatigue failure has a typical characteristic appearance. It is generally a smooth surface and frequently shows concentric rings or areas spreading from the point where the crack initiated. These rings show the propagation of the crack which might be related to periods of high stress followed by periods of inactivity. The fracture surface also tends to become rougher as the rate of propagation of the crack increases. Figure 23-25 shows the characteristic fatigue failure surface.

FIGURE 23-25 **Fatigue fracture surface.**

It was pointed out previously that many structures are designed to a permissible static stress based on the yield point of the material in use and the safety factor that has been selected. This is based on statically loaded structures, the stress of which remains relatively constant with respect to time. Many structures, however, are subjected to other than static loads in service. They are loaded by various live loads applied in different ways, for example, that caused by cyclic loading as in the case of a rotating device or of a bridge carrying varying traffic, or dynamic loads from machinery, or loads based on temperature changes, vibrations, and so on. These changes may range from simple cyclic fluctuations to completely random variations. In this type of loading the structure must be designed for dynamic loading and considered with respect to fatigue stresses.

The varying loads involved with fatigue stresses can be categorized in different manners. These can be alternating cycles from tension to compression. Or they can be pulsating loads with pulses from zero load to a maximum tensile load, or from a zero load to a compressive load, or loads can be high and rise higher, either tensile or compressive. In addition to the loadings, it is important to consider the number of times the weldment is subjected to the cyclic loading. For practical purposes, loading is considered in millions of cycles. Fatigue is a cumulative process and its effect is in no way healed during periods of inactivity. Testing machines are available for loading metal specimens to millions of cycles and the results are plotted on stress vs cycle curves, which show the relation between the stress range and the number of cycles, for the particular stress used. Fatigue test specimens are machined and polished and the results obtained on such a specimen may not correlate with actual service life of a weldment. It is therefore important to determine those factors which adversely affect the fatigue life of a weldment.

The possibility of a fatigue failure depends on four factors:

1. The material used
2. The number of loading cycles
3. The stress level and nature of stress variations
4. Total design and design details

It is this last factor that is controllable in the design and manufacture of the weldment. The problem of uniform distribution of stress throughout the cross-sectional area of a section was discussed previously. It was brought out that weld joints can be designed for uniform stress distribution utilizing a full-penetration weld, but in other cases joints may not have full penetration because of an unfused root and this prohibits uniform stress distribution. Even with a full-penetration weld if the reinforcement is excessive a portion of the stress will flow through the reinforced area and will not be uniformly distributed. It was brought out previously that welds designed for full penetration might not have complete penetration because of workmanship factors such

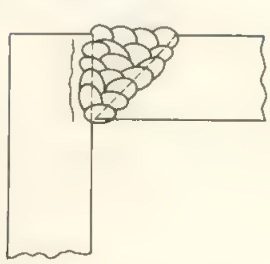
as cracks, slag inclusions, incomplete penetration, etc. and therefore contain a stress concentration. One reason fatigue failures in welded structures occur is because the welded design can introduce more severe stress concentrations than other types of design. The weld defect, including excessive reinforcement, undercut, or negative reinforcement, will contribute to the stress concentration factor. In addition, a weld forms an integral part of the structure and when parts are attached by welding they may produce sudden changes of section which contribute to stress concentrations under normal types of loading.

Anything that can be done to smooth out the stress flow in the weldment will reduce stress concentrations and make the weldment less subject to fatigue failure. Total design with this in mind and careful workmanship will greatly eliminate this type of a problem. See Ref. 4 for more information on fatigue failure.

Lamellar Tearing

Lamellar tearing is a relatively new term which has come into prominence because of some failures in structural steel work in buildings and in offshore drill rigs and platforms. Lamellar tearing is cracking which occurs beneath welds and is found in rolled steel plate weldments. The tearing always lies within the base metal, usually outside the heat-affected zone and generally parallel to the weld fusion boundary. Lamellar tearing is not new, but the term is. This type of cracking has been found in corner joints where the shrinkage across the weld tended to open up in a manner similar to lamination of plate steel. In these cases, the lamination type crack is removed and replaced with weld metal. Unfortunately, before the advent of ultrasonic testing this type of failure was probably occurring and was not found. It is only when welds subjected the base metal to tensile loads in the z or through direction of the rolled steel that the problem is encountered. For many years the lower strength of rolled steel in the through direction was recognized and the structural code prohibited z-directional tensile loads on steel spacer plates. Figure 23-26 shows how lamellar tearing will come to the surface of the metal. Figure 23-27 showing a tee joint is a more common type of lamellar tearing, which is much more difficult to find. In this case, the crack does not come to the surface and is under the weld. This type of crack can only be found with ultrasonic testing, or if failure occurs, the section can actually come out and separate from the main piece of metal.

FIGURE 23-26 Corner joint.



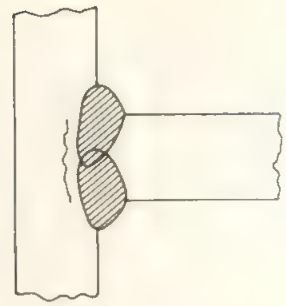


FIGURE 23-27 T joint.

Three conditions must occur to cause lamellar tearing:

1. Strains must develop in the through direction of the plate. These strains are caused by weld metal shrinkage in the joint and can be increased by residual stresses and by loading.
2. The weld orientation must be such that the stress acts through the joint across the plate thickness or in the z direction. The fusion line beneath the weld is roughly parrallel to the lamellar separation.
3. The material will have poor ductility in the through or z direction.

Lamellar tearing can occur during flame-cutting operations and also in cold-shearing operations. It is primarily the low strength of the material in the z or through direction that contributes to the problem. It is a stress placed in the z direction that triggers the tearing. The thermal heating and the stresses resulting from weld shrinking create the fracture. Lamellar tearing is not associated with the under-bead hydrogen cracking problem. It can occur soon after the weld has been made but on occasion will occur at a period months later. Also, the tears are under the heat-affected zone and it is seemingly more apt to happen in thicker materials and in higher-strength materials.

Only a very small percentage of steel plates are susceptible to lamellar tearing. There are only certain plates where the concentration of inclusions are coupled with the unfavorable shape and type that presents the risk of tearing. These conditions rarely occur with the other two factors mentioned previously. In general, the three situations must occur in combination: structural restraint, joint design, and the condition of the steel. The experience gained to date indicates that joint details can be changed to avoid the possibility of lamellar tearing. In the case of T joints it appears that double-fillet weld joints are less susceptible than full-penetration welds. In addition,

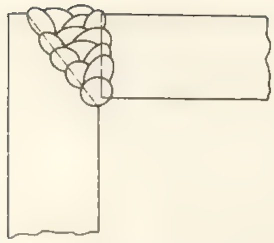


FIGURE 23-28 Redesigned corner joint to avoid lamellar tearing.

balanced welds on both sides of the joint appear to present less risk than large single-sided welds.

Corner joints are common in box columns. Lamellar tearing at the corner joints is readily detected on the exposed edge of the plate. The easy way of overcoming the problem of corner joints is to place the bevel for the joint on the edge of the plate that would exhibit the tearing rather than on the other plate (Figure 23-28).

Butt joints rarely are a problem with respect to lamellar tearing since the shrinkage of the weld does not set up a tensile stress in the thickness direction of the plates.

Experience has indicated that the arc welding processes having the higher heat input are less likely to create lamellar tearing. This may be because of the fewer number of applications of heat and the lesser number of shrinkage cycles involved in making a weld. It is also found that the deposited filler metal with lower yield strength and high ductility seemingly reduces the possibility of lamellar tearing. It does not appear that preheat is specifically advantageous with respect to lamellar tearing. Also, stress-relief heat treatment does not appear to have any beneficial effect. As a last resort, the buttering technique of laying one or more layers of low-strength high-ductility weld metal deposit on the surface of the plate stressed in the *z* direction will materially reduce the possibility of lamellar tearing. This is perhaps an extreme solution and should only be used as a last resort. The steel companies are attempting to initiate improvements in steel processing to avoid lamellar tearing. However, by observing the design factors just mentioned, the lamellar tearing problem is reduced. More information regarding lamellar tearing can be found in Ref. 5.

Stress Corrosion Cracking

Stress corrosion cracking and delayed cracking due to hydrogen embrittlement can both be troublesome when the weldment is subjected to the type of environment that accentuates this problem. Delayed cracking is caused by hydrogen absorbed in the base metal or weld metal at high temperatures. Liquid or molten steel will absorb large quantities of hydrogen. As the metal solidifies it cannot retain all of the hydrogen and it is forced out of solution. The hydrogen coming out of the solution sets up high stresses and if sufficient amount of hydrogen is present it will cause cracking in the weld or the heat-affected zone. These cracks develop over a period of time after the weld is completed. The concentration of hydrogen and the stresses resulting from it when coupled with residual stresses promote cracking, cracking will be accelerated if the weldment is subjected to thermal stresses due to repeated heating and cooling.

Stress corrosion cracking in steels is sometimes called *caustic embrittlement*. This type of cracking takes place when hot concentrated caustic solutions are in contact with steel that is stressed in tension to a relatively high level. The high level of tension stresses can be created by loading or by high residual stresses. Stress corrosion cracking will occur if the concentration of the caustic solution in contact with the steel is sufficiently high and if the stress level in the weldment is sufficiently high. This situation can be reduced by reducing stress level and reducing the concentration of the caustic solution. Various inhibitors can be added to the solution to reduce the concentration. A practical solution is to reduce the tensile stress of the area in contact with the corrisive solution. On piping this can be done by making weld beads on the outer surface, which causes compressive stresses on the inside-diameter surface.

Another type of cracking is called *graphitization*. This is caused by long service life exposed to thermal cycling, that is, repeated heating and cooling. This may cause a breakdown of carbides in the steel into small areas of graphite and iron. This formation of graphite, in the edge of the heat-affected area, exposed to the thermal cycling causes cracking. It will more often occur in carbon steels deoxidized with aluminum. The addition of molybdenum to the steel tends to restrict graphitization and for this reason carbon molybdenum steels are normally used in high-temperature power plant service. These steels must be welded with filler metals of the same composition.

23-5 WELDING—PAINTING

There are two other welding problems that require some explanation and solutions. These are welding over painted surfaces and painting of welds.

In general, the practice of welding over paint should be discouraged. In every code or specification it is specifically stated that welding should be done on clean metal. In some industries, however, welds are made over paint and in others flame cutting is done on painted base metal.

In the shipbuilding industry and in other industries, steel, when it is received from the steel mill, is shot blasted, given a coating of prime paint, and then stored out of doors. Painting is done to preserve the steel during storage, and also to identify it. In some shipyards a different color paint is used for different classes of steel.

When this practice is used every effort should be made to obtain a prime paint that is compatible with welding. There are at least three factors involved with the success of the weld when welding over painted surfaces:

- The compatibility of the paint with welding
- The dryness of the paint
- The paint film thickness

Paint compatibility varies according to the composition of the paint. Certain paints contain large amounts of aluminum or titanium dioxide and these paints are usually compatible with welding. Other paints may contain zinc, lead, vinyls, and other hydrocarbons, and are not compatible with welding. The paint manufacturer or supplier should be consulted. Anything that contributes to deoxidizing the weld such as aluminum, silicon, or titanium will, in general, be compatible. Anything that is a harmful ingredient such as lead, zinc, and hydrocarbons will be detrimental. The fillet break test can be used to determine compatibility. The surfaces should be painted with the paint under consideration. The normal paint film thickness should be used, and the paint must be dry. The fillet break test should be run using the proposed welding procedure over the painted surface. It should be broken and the weld examined. If the weld breaks at the interface of the plate with the paint it is obvious that the paint is not compatible with the weld. The paint supplier should be consulted since there are some paints that are compatible with welding.

The dryness of the paint should be considered. Many paints employ an oil base which is a hydrocarbon. These paints dry slowly since it takes a considerable length of time for the hydrocarbons to evaporate. If welding is done before the paint is dry hydrogen will be in the arc atmosphere and can contribute to underbead cracking. The paint will also cause porosity if there is sufficient oil present. Water-based paints should also be dry prior to welding.

The thickness of the paint film is another important factor. Some paints may be compatible if the thickness of the film is in the neighborhood of 3 to 4 mils maximum. If the paint film thicknesses are double that amount, such as occurs at an overlap area, there is the possibility of weld porosity. Paint films that are to be welded over should be of the minimum thickness possible.

Tests should be run with the maximum film thickness to be used, but dry, with the various types of paints to determine which paint has the least harmful effects on the weld deposit.

Cutting painted surfaces with arc or flame processes should be done with caution. Demolition of old structural steel work that had been painted many, many times with flame-cutting or arc-cutting techniques can create health problems. Cutting through many layers of lead paint will cause an abnormally high lead concentration in the immediate area and will require special precautions such as extra ventilation or personnel protection. Please refer to Chapter 3 for more information on safety precautions.

Painting over welds is also a problem. The success of any paint film depends on its adherence to the base metal and the weld. This is influenced by surface deposits left on the weld and adjacent to it. Paint failure occurs when the weld and the immediate area are not properly cleaned prior to painting. Deterioration of the paint over the weld also seems to be dependent upon the amount of spatter present. Spatter on or adjacent to the weld leads to rusting of the base material under the paint. It seems that the paint does not completely adhere to spatter and some spatter does fall off in time leaving bare metal spots in the paint coating.

The success of the paint job can be ensured by observing both preweld and postweld treatment. Preweld treatment found most effective is to use antispatter compounds, as well as cleaning of the weld area, before welding. The antispatter compound extends the paint life because of the reduction of spatter. The antispatter compound must be compatible with the paint to be used. This treatment thus reduces spatter, which insures a better success for the paint film.

Postweld treatment for ensuring paint film success consists of mechanical and chemical cleaning. Mechanical cleaning methods can consist of hand chipping and wire brushing or power wire brushing, or sand or grit blasting. Sand or grit blasting is the most effective mechanical cleaning method. If the weldment is furnace stress relieved and then grit blasted, it is prepared for painting. When sand or grit blasting cannot be used power wire brushing is the next most effective method. In addition to the mechanical cleaning, a chemical bath washing is also recommended. Slag coverings on weld deposits must be thoroughly removed from the surface of the weld and from the adjacent base metal. Different types of coatings create more or less problems in their removal and also with respect to paint adherence. Weld slag of many electrodes is alkaline in nature and must be neutralized to avoid chemical reactions with the paint which will cause the paint to loosen and deteriorate. The weld should be scrubbed with water, which will usually remove the residual coating slag and smoke film from the weld. If a small amount of phosphoric acid up to a 5% solution is used it will be more effective in neutralizing and removing the slag. However, if this is used it should be followed by a water rinse. If water only is used, it is advisable to add small amounts of phosphate or chromate inhibitors to the water to avoid rusting which might otherwise occur.

It has been found that the method of applying paint is not an important factor in determining the life of the paint over welds. The type of paint employed must be

suitable for coating metals and proper for the service intended.

Successful paint jobs over welds can be obtained by observing the following:

1. Minimize weld spatter.
2. Mechanically clean the weld and adjacent area.
3. Wash the weld area with a neutralizing bath and rinse.

QUESTIONS

23.1. What causes arc blow?

23-2. Why is alternating-current welding less likely to encounter arc blow?

23-3. What is the final solution to arc blow when parts are magnetized?

23-4. If a metal piece is not restrained, will it come back to its original dimension after heating?

23-5. Is heating uniform in metal during welding? Does this cause distortion?

23-6. Is a weldment restrained? Does this cause warpage?

23-7. What is plastic deformation? How is it affected by heat?

23-8. How can angular distortion be reduced?

23-9. Explain the reason for the special order of making weld joints on a tank.

23-10. What is the stress level of residual stresses?

23-11. How do residual stresses build up and change in a multipass groove weld?

23-12. How can residual stresses be reduced?

23-13. What is the danger of brittle fracture?

23-14. How is the type of failure determined?

23-15. What is the characteristic of a fatigue fracture? What four factors are involved?

23-16. Describe lamellar tearing.

23-17. What causes stress corrosion cracking?

23-18. How can this be overcome on piping?

23-19. What is the hazard of flame cutting old structures that are covered with many layers of paint?

23-20. What is required to obtain a good paint job over welds?

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24

Maintenance and Repair Welding and Surfacing

OUTLINE

24-1 WELD FAILURE ANALYSIS

Failures of welded structures are very rare. Catastrophic failures of major structures with the details and results of investigations are usually reported. These reports are useful since they provide information that is helpful in avoiding future similar problems. There are occasional failures of welds and weldments that should be investigated.

It is important to make an objective study of failures of parts or structures to determine the cause. This is done by investigating the service life, the conditions that led up to the failure, and the actual mode of the failure. An objective study of failure should utilize every bit of information available, should investigate all factors that could remotely be considered, and should evaluate all this information to arrive at the reason for the failure.

Failure investigation quite often will uncover facts that will lead to changes in design, manufacturing, or operating practice that will eliminate similar failures in

the future. Each failure and subsequent investigation will lead to changes that will assure a more reliable product in the future.

Failure analysis is required to establish the cause of the failure and determine the responsibility for the failure. The investigator should use extreme care and should present the facts in a logical order. The following four areas of interest should be investigated to determine the cause of the failure and the interplay of factors involved.

1. *Initial observation.* Investigators should make a detailed study of the actual component that failed. This should be made at the failure site as quickly as possible. Photographs should be taken, in color, of all parts, structures, failure surfaces, fracture texture appearance, final location of component debris, and all other factors. Witnesses to the failure should all be interviewed and all information determined from them should be recorded.
2. *Background data:* Investigators should gather all information concerning specifications, drawings, component design, fabrication methods, welding procedures, weld schedules, repairs in and during manufacturing and in service, maintenance, and service use. Particular attention should be given to environmental details, including operating temperatures, normal service loads, overloads, cyclic loading, abuse, etc.
3. *Laboratory studies.* Investigators should make laboratory tests to verify that the material in the failed parts possess the specified composition, mechanical properties, dimensions, etc. Micrographic studies should also be made. Each failed part should be thoroughly investigated to determine what bits of information it can add to the total picture. Fracture surfaces can be extremely important. Original drawings should be obtained and marked showing failure locations. This should be coupled to design stress data originally used in designing the product. Other defects in the structure that are apparent, even though they might not have contributed to the failure, should also be noted and investigated.
4. *Failure assumptions.* Investigators should list not only all positive facts and evidence that may have contributed to the failure, but also all negative responses that may be learned about the failure. It is sometimes as important to know what specific things did not happen or what evidence did not appear to help determine what happened. These data should be tabulated. The actual failure should be synthesized to include all available evidence. This might lead to the need for collecting additional data or asking more questions.

The true cause of failure will emerge by means of this study. Assumptions must be challenged by every bit of information available until it stands up as the one and only plausible cause for the failure. Failure cause can usually be classified in one of the following three classifications:

1. Failure due to faulty design or misapplication of material
2. Failure due to improper processing or improper workmanship
3. Failure due to deterioration during service

The following is a summary of these three situations.

Failure due to faulty design or misapplication of the material involves failure due to inadequate stress analysis, or a mistake in design such as incorrect calculations on the basis of static loading instead of dynamic or fatigue loading. Ductile failure can be caused by a load too great for the section area or the strength of the material. Brittle fracture may occur from stress risers inherent in the design, or the wrong material may have been specified for producing the part, or the weld joint is improper.

Failures can be due to faulty processing or poor workmanship. The quality of the weld is substandard. Failures can be attributed to poor fabrication practice such as the elimination of a root opening, which may cause incomplete penetration. There is also the possibility that incorrect filler metal was used.

One of the major problems is the problem of overload. Normal wear and abuse to the equipment may have resulted in reducing sections to the degree that they no longer can support the load. Corrosion due to environmental conditions and accentuated by stress concentrations will contribute to failure. There may be other situations such as poor maintenance, poor repair techniques and accidental conditions beyond the user's control. Or, the product might be exposed to an environment for which it was not designed. The reason for the investigation is to determine the cause of the failure.

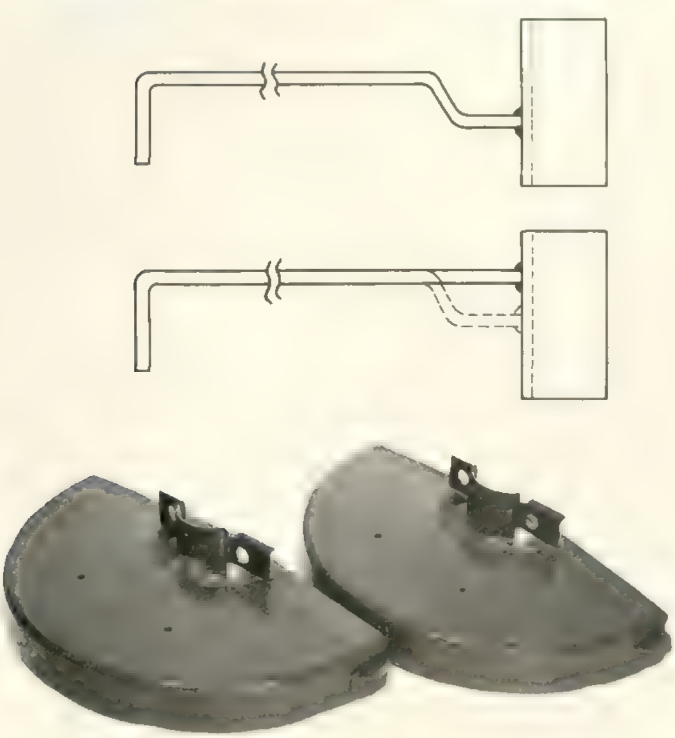
Failure Analysis Examples

There have been investigation reports made of many, many failures. Thorough investigations are always made if there is a loss of life. Governmental agencies are required to investigate failures of specific products. The Federal Aviation Agency always investigates aircraft accidents, the Office of Pipeline Safety determines the cause of pipeline failures, and the Department of Transportation investigates serious railroad and highway catastrophes. Informative investigations help advance the level of knowledge in a particular field. An example is the documentation of the Comet airplane failures.[1] This represented an outstanding example of a study and experi-

mentation necessary to track down the cause of failure. This investigation provided knowledge regarding the fatigue problems involved with aircraft structures. Another important failure analysis report, is the "Brittle Failure in Carbon Steel Plate Structures Other Than Ships."(2) This investigation provided insight into the failure mode of large welded structures. It repeated the fact that weldments are monolithic structures, that a welded structure is one piece of metal that may have designed into it internal and external notches, stress risers, and crack starters, and that stresses are distributed throughout weldments because they are monolithic structures, whether the designer had this in mind or not. Other investigations brought out this same fact.

Figure 24-1 shows an excellent example of a small welded part that failed and how it was modified and improved after an investigation pinpointed the problem. This part is a guard for a V-belt sheave of a gasoline-engine-driven garden tractor. Vibration and loading created premature failure of the weld joining the sheet metal part to the curved collar that clamped around the main shaft bearing. The curved collar was in intimate contact with the bearing and clamped solidly to it. The sheet metal section, which was flanged at the edge and subjected to a vibration loading both up and down, would tend to concentrate the stress at the toe of the fillet weld joining the two parts. The cross-section drawing shows the detail of the weld joint. It was soon realized that the vibration created the concentration at the toe of the weld based on the relative motion between the curved collar and the sheet metal guard. The solution of this problem was to form the sheet metal part so that the junction between it and the curved collar was extended over a greater distance so that the stresses would not be concentrated at one point of the weld. This was done by making the center portion of the sheet metal guard extend straight to the curved collar while allowing the remaining portion to be formed down to where it meets the curved collar in the same manner as the initial design. This meant that the weld was extended about ¾ in. (19.0 mm): the stress concentration was not at the toe of the weld in a single plane. By making this change, the problem was solved and the reliability of the product was greatly improved. This is a simple problem and solution, but it illustrates the changes that can be made to overcome design problems through an objective investigation and analysis.

FIGURE 24-1 **Redesigned part to overcome failure.**



This next example is of a failure in a larger and much more expensive weldment. A diesel-driven power shovel with a three-cubic-yard dipper was digging taconite from an open pit mine in the Mesabi range in northern Minnesota. On a mid-January day when the temperature was −20 °F (−29 °C) the boom failed without warning while the shovel was digging. The failure was complete since the point of the boom broke off completely about midway between the shipper shaft bearing and the point of the boom (Figure 24-2). This was a brittle failure since there was no deformation or necking down of the material thickness. The normal working stresses on this portion of the boom are compressive since the normal working load involved is the load transmitted by the hoist cable over the point sheave on the end of the boom. When the boom *swings*, that is, the machine rotates, there is a bending moment on the boom point section. Possibly the severest load is caused by the pull of the dipper as it goes through the heavy blasted ore. During this period the boom shakes and vibrates violently. The calculated stresses when combined were within the allowable limit.

The boom is a rectangular cross section varying in dimensions by about 16 in. (424 mm) by 20 in. (526 mm) at the location of the fracture. It was made of low-carbon mild steel. Investigation revealed that the notch bar impact properties of this steel were poor. The boom is made of two formed half-sections joined longitudinally by submerged arc welds. A ⅜-in. (9.5-mm) by 1-in. (25.4-mm) backup bar was used under the submerged arc welds. The point section was made as a subassembly and butt welded to the main section using the manual shielded metal arc process using E6012 electrodes. A diaphragm was located very near this butt welded joint. The boom was not stress relieved.

The fracture was initiated at the fillet weld attaching the diaphragm to the box section and at a point of poor root fusion in the transverse butt weld. The termination of the backup bars contributed to the stress concentration in the failure area. It was concluded that the stresses were concentrated at this area because of the abrupt end

FIGURE 24-2 Power shovel boom failure.

of the backing bars, the fillet weld joining the diaphragm to the box section, and the unfused root of the butt transverse weld. The base metal and the E6012 weld metal both have relatively poor low-temperature impact resistance. The low ambient temperature and the shock loading plus the stress concentration and the poor low-temperature toughness of the steel caused the failure.

The steps taken to avoid future similar failures were (1) to change to a low-alloy steel with better low-temperature impact toughness, (2) to change to E6015 electrodes, which possess better properties than the E6012, (3) to taper the ends of the submerged arc backup bars, and (4) to initiate root pass inspection on the transverse butt weld. These measures solved the problem, which did not reoccur on later booms.

Early in World War II, welded merchant vessels built in the United States experienced difficulties in the form of fractures which could not be explained. Many of these fractures occurred with explosive suddenness and exhibited a quality of brittleness which was not associated with the behavior of normally ductile materials used. Immediate steps were taken to investigate and solve the problem. A board of investigation was appointed to solve the problem by making a complete investigation and reporting the facts as established. "The Design and Method of Construction of Welded Steel Merchant Vessels"[3] is the most comprehensive report produced. The investigation took over three years, starting in April 1943 and concluding in July 1946. The investigation involved a total of 4694 ships, of which 970 sustained some type of structural casualty. Eight ships were lost at sea, four others broke in two but were not lost. Twenty-six lives were lost.

The study to analyze the failures involved design studies of each type of vessel involved, loading and ballasting conditions, convoy routes with accompanying sea and weather conditions, and extensive laboratory research aimed at studying fabrication and materials used in construction of the welded ships. The results of this effort to eliminate the occurrence of hull fractures were successful. The number of fractures decreased sharply after remedial measures were taken based on the findings of the board of inquiry.

The following is a summary of the findings:

1. The highest incidence of fracture occurred under the combination of low temperatures and heavy seas.
2. The age of the vessel had no appreciable influence on the tendency to fracture.
3. The loading and ballasting system did not create abnormal bending moments.
4. There was no marked correlation between the incidence of fracture on the ships and the construction practices of shipyards. It was found, however, that ships constructed in yards utilizing subaverage construction practices showed a higher-than-average incidence of fractures.
5. The bulk of failures were reported on Liberty ships, with only relatively fewer serious fractures on the Victory ships. (Victory ships were designed with fewer structural notches.)
6. The steel supplied for ship construction complied with the applicable specification for ship steel.
7. Locked-in stresses in the decks of completed vessels were not appreciably reduced in service.
8. Welding sequence in general had no effect upon the magnitude of residual welding stresses.
9. Every fracture examined started at a geometrical discontinuity or notch resulting from unsuitable design or poor workmanship.
10. There is a large variation in the notch sensitivity of steels used in ship construction. Steel removed from fractured vessels showed high notch sensitivity.

The investigators researched failures of riveted ships that had previously been reported. They found that when a crack starts in a riveted ship it generally progresses only to the first break in the continuity of the metal; that is, a riveted seam. There it awaits reloading to a stress which will give it a fresh start. In a welded structure, the crack will continue to propagate as long as sufficient energy is available.

A particularly bewildering phenomenon in the welded ship casualties was the appearance and nature of the fracture. It had been generally believed that medium ship steel would deform elastically when loaded within the elastic limit and that if it were loaded beyond that point plastic flow would take place and a permanent deformation would result as evidenced by a reduction in thickness or area. It was previously believed that if the load were increased sufficiently, material would fail only after considerable elongation. It was found on examining the ship fractures that the fractured surface appeared crystalline, rather than silky as it would in a ductile failure. The break was square and the line of separation normal to the surface of the plate. Very little ductility was evidenced as indicated by practically zero reduction in the thickness of the plate at the fracture. This type of fracture is termed a cleavage fracture, denoting a separation of the surface of the crystal lattice rather than sliding action along slip planes.

Early in the investigation, the designs were recalculated. The calculation showed that the hull girder strength was ample and that the margin of strength in the structure was over that required by the design standards. The monolithic character of the welded ship produced specific areas that have high stress concentrations and severe restraint that inhibit plastic flow. This condition did not exist generally in riveted ships. The danger of high concentration at points of structural discontinuities in the welded ship is further aggravated by the welds usually present at such points. The welding produces a complex metallurgical condition, which is sometimes aggravated by discontinuities in the form of defects in the welds. The design of a ship hull requires numerous openings, machinery foundations, deck houses, and so on. At each of these points of structural discontinuity the section modulus change abruptly, and when under a bending load, a stress concentration occurs. Stress concentrations of dangerous magnitude exist at structural discontinuities such as the hatch corners, shear strake cutouts, and at the point where foundations and deck houses are welded to the deck. Investigation found that most of the serious fractures started at hatch corners and many started in the shear strake cutout for the accommodation ladder. This strongly emphasized that insufficient attention was paid to the elimination of discontinuities or notches whether they be large or small and that the effect of these discontinuities is aggravated by the monolithic character of welded construction. At the time when the investigation started the mechanism of metal fracture was not well understood. The incidence of serious failures of large welded steel structures, both during construction and during service, indicated the need for a better understanding of the fundamental factors affecting steel performance. Lack of reliable information had led designers to overdesign in the interest of safety, which in some cases enhanced the possibility of failure. Impact tests of steel samples taken from vessels which suffered fractures indicated that in many cases the steel was notch sensitive. That is, its ability to absorb energy in the notched condition especially at low temperatures was low. The research investigators explored the behavior of ship steel in the welded and unwelded condition and under the influence of multiaxial stress in the presence of discontinuities such as notches, especially at low temperatures. These studies found that *notch sensitivity* was an important factor in the occurrence of *brittle* failures.

The welding subcommittee made a survey of shipyards and found varying degress of quality in workmanship and in methods of construction. The analysis of structural failures did not indicate a marked correlation between the incidence of fractures in welded ships in shipyard construction practice; however, ships produced in those yards utilizing below-average practices showed a

higher-than-average incidence of failure. It was concluded that high-quality workmanship is important in building welded ships. They felt that welds should be identified as to who made the weld and that there should be an improvement of welder training and upgrading. They also felt that welding sequences and procedures must be prepared and the work must follow them. They did conclude that evidence was found to indicate that locked-in stresses or residual welding stresses were important in causing the fractures.

The board concluded that the fractures in welded ships were caused by notches and by steel that was notch sensitive at operating temperatures. When an adverse combination of these occur, the ship may be unable to resist the bending stresses of normal service.

Figure 24-3 shows the Liberty ship and details with abnormal frequency of fractures. Figure 24-4 shows the tragic results of the S.S. *Schenectady* breaking in two at the outfitting dock prior to being placed in service.

The epidemic of fractures was greatly reduced through the combined effect of corrective measures taken on the structure of the ship during construction and after completion, improvements in new design, and improved construction practices in the shipyards. The first remedial step taken was to eliminate stress concentration of cargo hatch openings. This was done by modifying the corners to provide rounded corners rather than sharp or square corners. Various types of *crack arrestors* were installed.

This exhaustive examination of catastrophic and major failures led designers to appreciate the fact that weldments are monolithic in character, that anything welded onto a structure will carry part of the load whether intended or not; also, that abrupt changes in section, either because of adding a deck house or removing a portion of the deck for a hatch opening, create stress concentration. Under normal loading, if the steel at the point of stress concentration is notch sensitive at the service temperature, failure can result.

It was reported by the board that the results of the investigation have vindicated the all-welded ship. The statistics show that the percentage of vessels sustaining serious fracture is small. With proper design, high-quality workmanship, and steels that have good notch sensitivity at operating temperatures, a satisfactory all-welded ship can be obtained. This was further reinforced by the fact that the Victory ships, which were designed to reduce stress concentration, sustained fewer and less serious fractures. Novels have even been written about failure investigations. One of the most famous was about an airplane crash.[4]

FIGURE 24-3 Liberty ship: location of fractures.

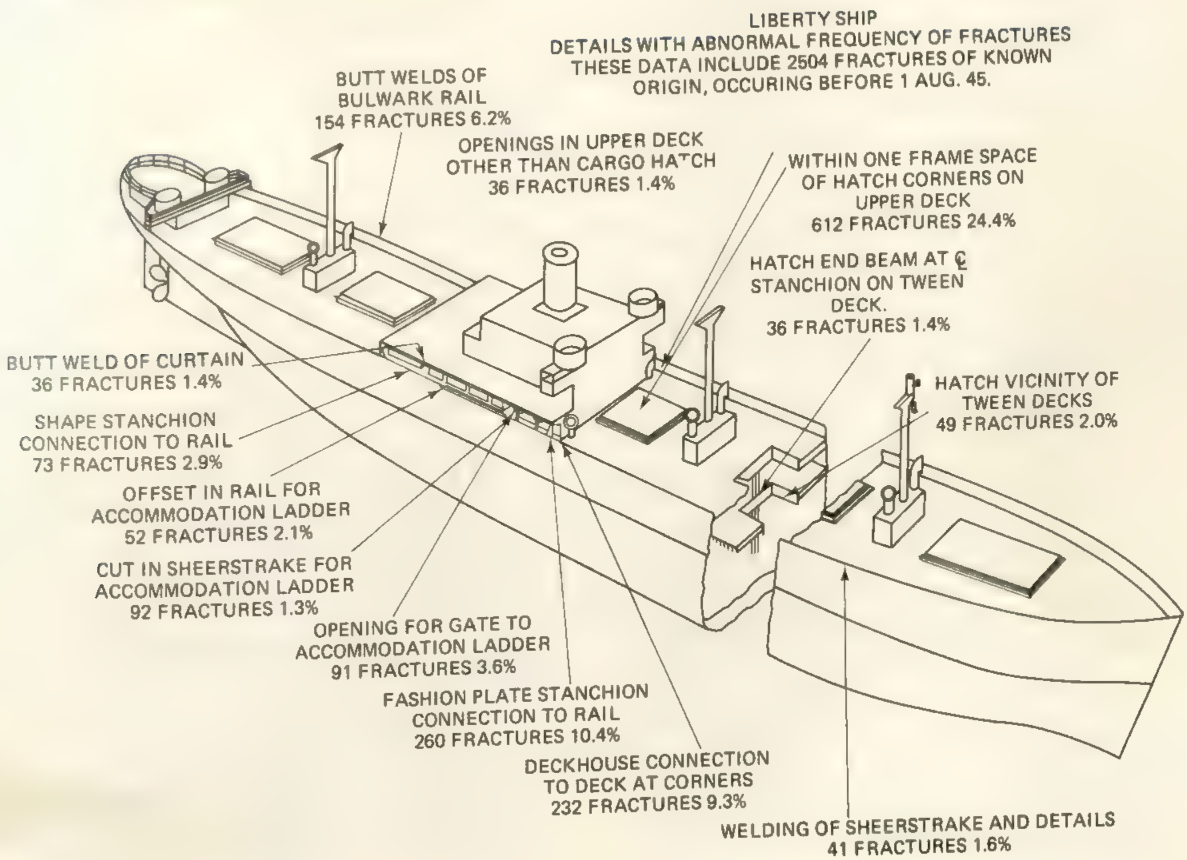


FIGURE 24-4 S.S. *Schenectady* after splitting in two at dock.

A thorough analysis as outlined may not be required in some situations. This is due to experience gained in analyzing jobs, making repairs, and then checking on the service life of the repaired part. As experience is gained, shortcuts can be taken. The reasons for an investigation is to establish the cause of the failure in the case of a broken part, or the cause of wear or erosion in the case of a part to be surfaced.

24-2 DEVELOP REWORK PROCEDURE

The success of a repair or surfacing job depends on the thought and preparation prior to doing the work. Parts break and wear out and it may be impossible to obtain a replacement part. This is particularly true of older machinery. Metal surfaces deteriorate from corrosion, abrasion, erosion, and so on, until the part is no longer serviceable. Repairs are required and welding is the quickest and most reliable method for returning the part to service. Weld repair is often the most economical solution, especially when the "out of service" time depends on obtaining a new part. Replacement parts are often not immediately available, and if they are, they are very expensive. The economies of weld repairing are very favorable. Some weld repair jobs may only take a few minutes, and some complex structures may require weeks for proper preparation and welding.

Once the decision has been made to make a weld repair, it is then necessary to review why the part failed or wore out. This relates to the type of repair job since it indicates if reinforcing is required. Reasons for the part to fail or wear out can be among the following:

- ☐ Accident
- ☐ Misapplication
- ☐ Abuse
- ☐ Overload
- ☐ Poor design
- ☐ Incorrect material
- ☐ Poor workmanship

If the part failed because of an accident or an overload, it can be returned to service with the weld repair made to bring it back to its original strength. This applies also if the part has been abused or misapplied. It may be necessary to reinforce the part so that it will stand temporary overloads, misapplication, or abuse.

In the case of poor workmanship, the weld repair should rework the poor workmanship responsible for the failure. The part would be returned to its original condition. If failure is due to poor design, design changes are required and reinforcement may be added. In a case of incorrect material it is assumed that the material was of a lower strength level, which contributed to the failure. In this case reinforcing would be required. If the repair is to alter the part, it is necessary that the modification is designed by an experienced designer. Drawings and additional parts will be required. It is important that the repaired or reworked part meets or exceeds the characteristics of the original part.

An important factor is the type of repair work required. It can be a standardized, repetitive job such as the resurfacing of dipper teeth of an excavator or the rebuilding of track shoes of a crawler tractor. These are parts that routinely wear and must be repaired by weld-

ing on a scheduled basis. Or it can be a weld repair because of a breakdown, which is a one-of-a-kind job often an emergency. An example would be the broken power shovel boom shown previously. Emergency repair work must be analyzed quickly and a procedure established as soon as possible. Large machines, when down, create delays in an entire operation, such as a mine, and cost extremely large amounts of money while they are out of operation. This also applies to oil-drilling operations, offshore platforms, steel rolling mills, electric power generators, and other production equipment. These are the types of repair work where "return to service" is all important and there is no time to obtain a replacement part.

Investigate before Repairing

There are certain situations and certain types of equipment where repair welding should not be done or may be done only with prior approvals. It may be uneconomical to repair some parts. An example is the weld repair of a cast iron part that is repeatedly heated and cooled. Weld repairs on cast iron parts subjected to repeated heating and cooling may not provide adequate service life. The problem is that cast iron parts such as machinery friction brakes, furnace sections, and so on, failed originally from this kind of service. The metallurgical changes involved with the weld may not be able to withstand repetitive heating and cooling cycles. Such repairs should only be made on an emergency basis until replacement parts are available.

If a failure occurs when equipment is new and within the manufacturer's warranty, it is necessary to contact the original manufacturer of the equipment. The manufacturer must be made aware of the problem or failure and the repair that is planned. Failure to do this will cancel the machine's warranty.

Aircraft may be repaired by welding but only under stringent controls. The welder doing repair welding on aircraft should be qualified in accordance with MIL-T-5021D or latest "Tests; Aircraft and Missile Welding Operators Certification," on the type of metal being welded, using the process for which the welder is qualified, and on the category of parts involved. Furthermore, the welder should be certified in accordance with requirements of the Department of Transportation Federal Aviation Administration. The FAA issues two documents, "Acceptable Methods, Techniques and Practices—Aircraft Inspection and Repair"[5] and the "Air Frame and Power Plant Mechanics Air Frame Handbook."[6] Both provide precautionary information techniques, practices, and methods that may be used for repair welding. Techniques, practices, and methods other than those prescribed may be used provided that they are acceptable to the administrator of the Federal Aviation Administration. Extensive damage must not be weld repaired on items such as engine mounts, landing gear, or fuselage components unless the method of repair is specifically approved by an authorized representative of the FAA or the repair is accomplished in accordance with the FAA-approved instructions furnished by the aircraft manufacturer. The reason for these regulations is that many such parts are of high-strength material, and the strength is obtained by postweld heat treatment. Certain parts are not to be welded if the damage is beyond a specific amount. Consult with Federal Aviation Administration authorities or the manufacturer of the particular aircraft. For safety reasons welding must not be done on aircraft inside hangers, unless all fuel is completely removed and the aircraft is made inert.

Certain types of containers and transportation equipment must not be weld repaired or may be welded only with special permission and approval. These include railroad locomotive and railroad car wheels, high-alloy high-strength truck frames, and compressed gas cylinders.

Most power-generating machinery, including turbines, generators, and large engines, are covered by casualty insurance. Weld repair can be done only with the prior approval of the welding procedure by the insurance company. Approval may not be granted. An example of this would be a cast iron crankshaft in a large stationary diesel engine. In many cases weld repairs can be made, but it is necessary to develop a written procedure which must be approved in writing by the insurance company representative.

Alterations of bridges, large steel frame buildings, and ships may be done only with special authorization. The alteration work must be designed and approved. The welders must be qualified according to the code used and the work must be inspected. Written welding procedures are required.

Repairs to boilers and pressure vessels require special attention. The ASME Codes are for new construction. Repair, maintenance, or alterations are a jurisdictional responsibility. The "National Board Inspection Code"[7] has been adopted by most jurisdictional authorities in North America (cities, states, and provinces) to provide rules for inspection, maintenance, repairs, and alterations to boilers and pressure vessels. To maintain reliability and insurability, and ASME stamping on boilers and pressure vessels, the rules of National Board of Inspection Codes must be met and an authorized inspector must be involved during repairs and alterations.

The National Board Inspection Code defines basic and routine repairs and alteration. A repair is the work necessary to restore a boiler or pressure vessel to its original or to a safe and satisfactory operation condition. Alterations are any changes that affect the operation of the boiler or pressure vessel from its original design.

A written procedure is required for doing either repair work or alteration. All work must be performed

in a manner to maintain the original integrity of the ASME Code vessel. All welding procedures and welders must be qualified in accordance with ASME Section IX.

There are companies that specialize in the repair and alterations of boilers and pressure vessels. These companies must have authorization from the appropriate jurisdictional authority, or they must possess a current ASME Code Symbol Stamp covering the scope of the repair work, or they must possess a current National Board "R" Repair Code Symbol Stamp. In any case, where repair welding is performed the authorized inspector must be involved. The repair firm will contact the jurisdictional authority, the insurer, and the owner of the boiler or pressure vessel to assure that the method and extent of repair or alteration is given proper prior approval. This is required to ensure the proper continued use of the boiler or pressure vessel that is repaired or altered.

Alterations to boilers and pressure vessels require special attention. A statement must be obtained, from an ASME certificate holder with the appropriate scope, certifying that the redesigned portion of the alteration is correct. This certification of the design is made on the R-1 Alteration Form and must be accepted and signed-off by the ASME certificate holder's authorized inspector. This authorizes the repair company to proceed with the alteration. The alteration must include the involvement of the authorized inspector. In any case, the repair company must be an ASME certificate holder with the appropriate scope covering the alterations, or must have a National Board "R" stamp following the rules published in the National Board Inspection Code.

Rework Procedure

A written repair procedure is required for all but the simplest jobs. The composition of the material being welded must be known. If this is not possible, particularly in the field, look for clues as to the metal involved. Refer to Section 15-3 for help. As a final resort, obtain a laboratory analysis of the metal. Filings or a piece of the metal must be sent to a laboratory for analysis.

The normal method of selecting the welding process based on the type and thickness of the metal, the position of welding, and so on, should be followed. This aids selection of filler metal, which involves matching composition and properties to provide weld metal that will withstand the service involved.

In surfacing, the desired surface characteristics depends entirely on the service to which it will be exposed. Surfaces can be rebuilt many times without reducing the strength of the part, and the service life will be greatly extended.

The repair procedure should be very similar to a procedure developed for welding a similar part. It should include the process, filler metal, and the technique to be used in making welds. The format utilized by Section IX of the pressure vessel code can be utilized for repair procedures. The procedure, for complex jobs, should be qualified to determine that it will provide a repair weld that is equal in strength to the original part. This is done in the same manner as qualifying a welding procedure by a code. The repair procedure should be approved by the proper authority. This could be the inspector of a casualty insurance company, the inspector of the National Board, the representative of the manufacturer of the original equipment, or a governmental representative, such as the state piping or boiler inspectors. For work on ships, the shipping rating agency should be consulted. In every case consider the specification or code under which the product was built. In any case on extensive repairs on critical items, make sure that the procedure is practical and will provide the necessary-strength for the service intended. It is well to assume that written procedures and approvals are required prior to making any repair welds. Only after the procedure has been approved by all necessary parties is it time to make the repair weld.

24-3 MAKING THE REPAIR WELD

All factors have been reviewed and analyzed, and the decision has been made to repair by welding. The analysis indicated the cause of the failure, and the material composition is known. A repair welding procedure has been prepared and all involved have approved. The weld repair may be as simple as the removal and replacing of a body panel in an automobile or as complex as the repair of a rolling mill frame (Figure 24-5). In any case, there are three separate phases to the job:

1. Preparation for welding
2. Welding
3. Postweld operation

The amount of detail that must be considered depends on the complexity of the job.

Preparation for Welding

A large number of factors should be considered and decisions made before starting to weld.

1. *Safety*. The repair welding location must be surveyed and all safety considerations satisfied. This can include the posting of the area required by certain regulations, removal of all combustible materials from the area, the draining of fuel tanks of construction equipment, aircraft, boats, trucks, etc. The removal or inerting of any fuel pipeline, tanks, blind compartments, etc. If electrical cables are involved they should be removed or made inactive. Other precautions include the elimination of

FIGURE 24-5 Complex weld repair: rolling mill frame.

toxic materials such as thick coats of lead paint, plastic coverings of metals, etc. If heights are involved, proper scaffolding with safety devices should be used. If welding is enclosed, preparations for proper ventilation and personnel removal should be made. If these hazards cannnot all be removed, special safeguards should be established such as fire watch, wetting down, or protecting combustible wooden floors, etc. Traditionally, repair welding creates more safety problems than production welding, extra special precautions must be taken.

2. *Cleaning.* The immediate work area must be clean and this includes removal of dirt, grease, oil, rust, paint, plastic coverings, etc., from the surface of the parts being welded. The method of cleaning depends on the material to be removed and the location of the workpiece. For most construction and production equipment, steam cleaning is recommended. When this is not possible solvent cleaning can be used. Blast cleaning with abrasives is also used. For small parts pickling or solvent dip cleaning can be used and, finally, power tool cleaning with brushes, grinding wheels, disk grinding, etc., can be employed. The time spent cleaning a weld repair area will pay off in the long run.
3. *Disassembly.* Except for the most simple repair jobs disassembly may be required. This applies to lubrication lines, instrument tubing, wiring, etc. Sometimes it is necessary to disassemble major components. Experience with similar jobs is important, since it is expensive to disassemble and remove machinery when not required.
4. *Protection of adjacent machinery and machined surfaces.* When repair welding is done on machinery many parts that are not removed should be protected from weld spatter, flame cutting sparks, and other foreign material generated by the repair process. Sheet metal guards or baffles are used to protect adjacent machinery. For machined surfaces, cloth can be employed. It is wise to secure protective material with wire, clamps, tape, or temporary bracing. Machined surfaces within 5 feet of the welding operation should be protected.
5. *Bracing and clamping.* On complex repair jobs bracing or clamping may be required. This is because of the heavy weight of parts or the fact that loads may be exerted on the part being weld repaired. If main structural members are to be cut the load must be carried by temporary braces. The braces can be temporarily welded to the structure being repaired. The braces can be strong backs or pieces welded on both sides of the repair area to maintain alignment of the part while the repair weld is being made. If strong backs or bracing are used they should be located so that they do not interfere with the repair welding.

6. *Lay out repair work.* In most repair jobs it is necessary to remove metal so that a full-penetration weld can be made. A layout should be made to show the metal that is to be removed by cutting or gouging to prepare the part for welding. The minimum amount of metal should be removed to obtain a full-penetration weld. The layout should be selected so that welding can be balanced, if possible, and that the bulk of the welding can be made from the more comfortable welding position. The root opening should be specified, and if the welding can be done on the back side it should be gouged for full-penetration welding. If the back side cannot be reached for welding, backing straps should be employed. The groove angle should be the minimum possible for use but should be of sufficient size so that the welder has room to manipulate the arc at the root.
7. *Preheating.* Preheating and flame cutting or gouging is part of the preparation for welding but can be considered part of the welding operation. When flame cutting or gouging is required, preheat temperature should be the same as when welding. It is wise to preheat prior to cutting or gouging to at least one-half the temperature that will be used for the repair welding operation. Preheating should be based on the mass of the metal involved. If the mass is great heating should be slow so that thorough heating occurs. Surface heating is not acceptable. Preheating can be done by any of the normal methods; however, the slower processes would be advantageous. The equipment for preheating and sufficient fuel should be available prior to starting.
8. *Cutting and gouging.* The oxygen fuel gas cutting torch is most often used for this application. Special gouging tips are available and they should be selected based on the particular geometry of the joint preparation. It is possible, by closely watching the cut surface, to find and follow cracks during the flamegouging operation. The edges of the cracks will show since they become slightly hotter. The air carbon arc cutting and gouging process is also widely used for weld repair preparation. Proper power sources and carbons should be selected for the volume of metal to be removed. For some metals the torch or carbon arc might not be appropriate and in these cases mechanical chipping and grinding may be employed. Chipping is preferable to grinding and air power tools should be employed. The resulting groove should be smooth without reentrant gouges or notches.
9. *Grinding and cleaning.* The resulting surfaces may not be as smooth as desired and may include burned areas, oxide, etc. Grind the surfaces to clean bright metal prior to starting to weld. For critical work or where there is a suspicion of additional cracks it is wise to inspect the surface by magnetic particle examination to make sure that all defects have been removed.

The nine steps above should be followed for weld preparation. Some of these may be eliminated but they should all be considered to properly prepare the joint for welding.

Repair Welding

Successful repair welding involves following a logical sequence to make sure that all factors are considered and adequately provided for.

1. *Welding procedure.* The welding procedure must be available for the use of the welders. It must include the process to be used, the specific filler metals, the preheat required, and any other specific information concerning the welding joint technique. This procedure must be understood by all concerned. It should be written.
2. *Welding equipment.* All welding equipment should be available so that there will be no delays. Standby equipment might also be required. This should include sufficient electrode holders, grinders, wire feeders, cables, etc. Sufficient power must be available at the site to run all of the equipment required. In addition, if the job runs around the clock, provisions for lighting, personnel comforts such as wind breaks or covers, etc., should be provided.
3. *Materials.* Sufficient materials must be available for the entire job. This includes the filler metals for the repair. It also includes materials such as insert pieces, reinforcing pieces, etc., fuel for maintaining preheat and interpass temperature, shielding gases, and fuel for engine powered welding machines. If inspection equipment is required for intermediate checking, this equipment must also be available.
4. *Alignment markers.* Prior to making the weld alignment markers are sometimes used. These can be nothing more than center punch marks made across the joint in various locations. With precise measuring equipment such marks are useful in maintaining dimensional control and alignment during the welding operation. This is more important when repairing mechanical equipment than for structural applications.
5. *Welding sequences.* The welding sequence should be well described in the welding procedure and can include block welding, back-step sequence welding, wandering sequence welding, and peening. These techniques are useful to reduce distortion and to help maintain alignment and dimensional control. By making precision measurements from the check

points the technique can be varied to maintain alignment.

6. *Manpower.* There should be sufficient welders assigned to the job so that it can be completed quickly. Welders should be rotated so that they will be able to produce quality welds. Welders should not work excessive hours on precise jobs. Many jobs require three shifts of welders when the need to return to service is paramount.
7. *Safety.* Safety cannot be compromised throughout the entire operation. For example, ventilation must be provided when fuel gases are used for preheating, etc.
8. *Weld quality.* The quality of the weld should be continually checked. The final weld should be smooth, there should be no notches, and reinforcing, if used, should fair smoothly into the existing structure. If necessary, grinding should be done to maintain smooth flowing contours.

Postweld Operation

After the weld has been completed, it should be allowed to slow cool. It should not be exposed to winds or drafts, nor should the machinery loads be placed on the repaired part until the temperature has returned to the normal ambient temperature.

1. *Inspection.* The finished weld should be inspected for smoothness and quality. This can include nondestructive examination. The repair weld should be of high quality since it is replacing original metal of high quality.
2. *Clean up operation.* This includes the removal of strongbacks and the smooth grinding of the points where they were attached. It also involves the removal of other bracing and protective covers, etc. In addition, all weld stubs, weld spatter, weld slag, and other residue should be removed from the repair area to make it cleaner than it was originally. Grinding dust is particularly troublesome and every effort should be made to remove it entirely since it is abrasive and can get into working joints, bearings, etc., and create future problems.
3. *Repainting.* After the weld and adjacent repair area have been cleaned, they should be repainted and other areas should be regreased in preparation for the reoperation of the machinery.
4. *Reassembly.* The pieces of machinery that were taken away are returned for reassembly. Particular attention should be paid to the fit of machinery. If necessary, remachining or redressing should be done to assure proper fit. All other items, such as grease lines, cables, conduits, etc., should be reassembled, and once this has been done, the machinery should be tested prior to operation.

There is a gratifying sense of accomplishment of a successful repair job. Most complex repair jobs are done under much pressure due to the short time out of service.

Weld repair is an extremely technical subject and must be properly handled. On the other hand, it is a time-saver and an economic advantage. It requires greater-than-normal skills for successful jobs, but will pay off in the long run.

24-4 REBUILDING AND OVERLAY WELDING

Rebuilding and overlaying with weld metal or spray metal are both considered surfacing operations. Surfacing is the deposition of filler metal on a base metal to obtain desired dimensions or properties. Overlay is considered to be a weld or spray metal deposit that has specific properties sometimes unlike the original surface properties. Rebuilding is used on worn shafts, on parts that were machined undersize, and so on. Overlay surfacing is used to return the part to original dimensions but with the deposited metal having particular properties to reduce wear, erosion, corrosion, and so on.

Rebuilding and overlay, or the all-embracing term *surfacing* can be done by many of the welding processes and by the thermal spraying processes. There are some situations in which the thermal spray processes should be selected. The thermal spray processes do not introduce as much heat into the work as do the welding processes. It is possible to thermal spray certain materials that cannot be deposited with the welding processes, such as ceramic sprayed coatings.

The selection of the welding process and the welding procedure and technique is as important as the selection of the deposit alloy. The various factors discussed previously should be considered; however, there are additional factors. Whether the job is to be done in the field or in the shop has a definite bearing on process selection. In addition, if it cannot be moved and must be welded in place, the use of some processes is prohibited. The properties and analysis of the base metal also have an important bearing, as does the cost factor.

The shielded metal arc welding process is the most commonly used for hardfacing. Figure 24-6 shows the shielded metal arc process being used to surface a dredge cutter head.

Submerged arc welding is used for plant operations. It is often used for repeating applications when the same part is surfaced on a routine basis. Rollers, track shoes, and drums are commonly hardfaced with submerged arc welding. Figure 24-7 shows a power shovel ring gear being resurfaced. Over 400 lb of weld metal was deposited in this operation. Submerged arc using strip electrodes is sometimes used for overlaying surfaces in nuclear vessels with stainless steel to improve service life.

FIGURE 24-6 Surfacing a dredge cutter head with SMAW.

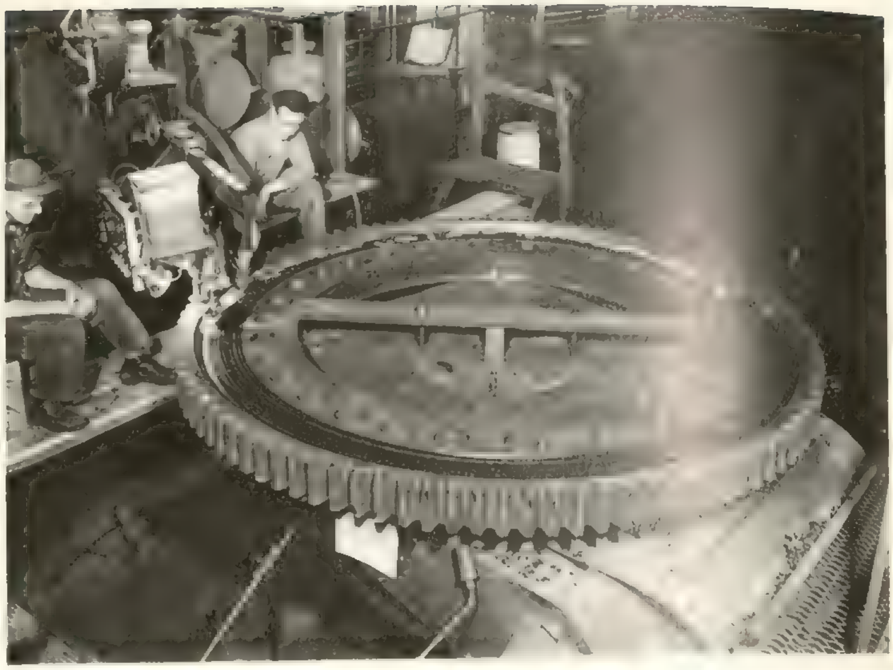


FIGURE 24-7 Surfacing a ring gear with submerged arc.

Flux-cored arc welding is popular in the shop and is not restricted to the flat position. Figure 24-8 shows the process being used in the field to build up a dipper lip.

The gas metal arc welding process is also used, but there is not as wide a selection of solid electrode wires available for hard-surfacing applications. It is used for buildup applications, either semiautomatically or fully automatic. Figure 24-9 shows the process being used on a small shaft.

FIGURE 24-8 Surfacing a dipper lip with flux cored arc welding.

The gas tungsten arc welding process is used for many smaller applications, usually in the shop. It is more expensive than the other processes and is restricted to nonferrous metals.

Plasma arc welding is also used in much the same manner as gas tungsten arc welding.

The electroslag welding process is used for special applications. It is widely used for rebuilding crusher hammers. These can be rebuilt with special fixturing and done quite rapidly with the electroslag process

Oxyacetylene welding is also used for certain applications.

In general, the process is selected based on normal process selection factors and modified by some of the

FIGURE 24-9 Surfacing a shaft with gas metal arc.

comments above. Once the process is selected, the next requirement is the selection of the deposited metal to provide the necessary properties.

Salvaging of Shafts

Rebuilding round shafting is an important application of surfacing. Worn or mismachined shafts can be salvaged by surfacing with the gas metal arc welding process. The same procedure can be used to provide an overlay with specific properties to improve its service life. Shafts exposed to corrosive atmospheres can be surfaced with stainless steel to improve service performance.

The gas metal arc welding process utilizing a small-diameter electrode is preferred to thermal spraying since it produces a weld. This is important since splines and keyways can be cut in weld deposits without harming the overlay.

Close adherence to the procedure is more important when the diameter of the part being welded is small. Figure 24-9 shows the GMAW process surfacing a relatively small diameter shaft. An old lathe or similar device can be used to provide rotation. Precautions should be taken to avoid welding current from passing through roller bearings. A rotary connection should be used. The welding gun can be mounted in the lathe toolholder. It should be offset approximately one-fourth of the diameter of the part being welded or at the 1:30 or 2-o'clock position. The offset is always toward the direction of rotation and the electrode should point to the centerline of the rotating part. The travel of the gun with respect to the longitudinal axis should be fast enough so that each weld bead blends smoothly into the preceding one. If the offset distance is insufficient, the molten metal will not solidify before it reaches the top of 12-o'clock position and may form a high crown bead. If the offset distance is too large, the molten weld metal may run down the shaft ahead of the arc. The angle of the gun can be adjusted to point slightly ahead up to 5°, to improve shielding gas coverage. Experience will assist in setting these exact distances based on different diameter parts.

The welding procedure must include the welding travel speed. On rotating parts this is known as surface inches per minute. The correct speed will ensure a smooth weld deposit that will require a minimum amount of machining. Figure 24-10 provides the method of determining the surface speed based on the diameter of the part and related to the rotational speed of the turning equipment. To determine the revolutions needed for the desired travel speed, draw a straight line between the diameter of the shaft and the desired travel speed. The desired travel speed is the 20 in./min. Where the line intersects revolutions per minute, read the rpm required. For example, with a 2-in.-diameter shaft to be welded, draw the line through 20 of the surface travel speed to the intersection with revolutions per minute, which would be

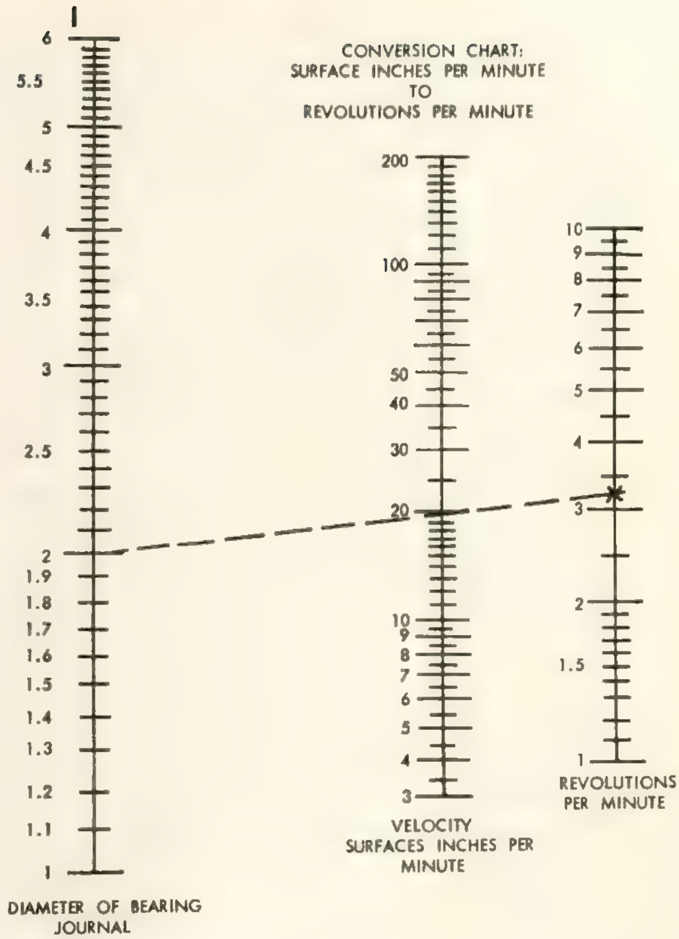


FIGURE 24-10 Conversion chart: in./min to rpm.

3.3. The 20-in./min surface speed is proper when using the 0.024-in.-diameter electrode wire in the range 120 to 150 A. For bigger jobs, larger electrodes can be used and the procedure variables will be different.

24-5 SURFACING FOR WEAR RESISTANCE

Wear

Wear is the result of impact, erosion, metal-to-metal contact, abrasion, oxidation, and corrosion, or a combination of these. The effects of wear, which is extremely expensive, can be repaired by means of welding. Surfacing with special welding filler metals is used to replace worn metal with new metal. Hardfacing applies a coating for the purpose of reducing wear or loss of material by abrasion, impact, erosion, oxidation, cavitation, etc. It can be used to extend the usable life of wear parts. It can save money since the replacement of worn parts is costly, particularly when the downtime and repair labor is considered.

The selection of a hardfacing material is extremely complex.

To select the proper hardfacing alloy it is necessary to understand the wear that caused the metal deterioration. The various types of wear can be categorized and defined as follows:

Impact wear is the striking of one object against another. It is a battering, pounding type of wear that breaks, splits, or deforms metal surfaces. A good example is the impact encountered by a tamper.

Abrasion is the wearing away of surfaces by rubbing, grinding, or friction. It usually occurs when a hard material is used on a softer material. It is usually caused by the scouring action of sand, gravel, slag, earth, or gritty material on machinery.

Erosion is the wearing away of materials by the abrasive action of a liquid. This type of action gouges or grooves out metal surfaces. This is also caused by steam and slurries that carry abrasive materials. Pump parts are subject to this type of wear.

Compression is a deformation type of wear caused by heavy static loads or by slowly increasing pressure on metal surfaces. Compression wear causes metal to move and lose its dimensional accuracy.

Cavitation wear results from turbulent flow of liquids, which carry suspended abrasive particles.

Metal-to-metal wear is a seizing and galling type of wear that rips and tears out portions of metal surfaces. It is often caused by metal parts seizing together because of lack of lubrication. Frictional heat helps create this type of wear.

Corrosion wear is the gradual eating away or deterioration of metal surfaces by the effects of the atmosphere, acids, gases, alkalies, and so on. This type of wear creates pits and perforations and may eventually dissolve metal parts.

Oxidation is a type of wear indicated by the flaking off or crumbling of metal surfaces. This takes place when unprotected metal is exposed to a combination of heat, air, and moisture. Rust is an example of oxidation.

Thermal shock is a problem indicated by cracking or splintering, which is caused by repeated rapid heating and cooling. Although not exactly a wear problem, it is a deterioration problem and is considered here.

Many of these types of wear occur in combination with one another. It is wise to look for a combination of factors that create the wear problem in order to best determine the type of hardfacing material to apply. This is done by studying the worn part, the job it does, how it works with other parts of the equipment and the environment in which it works.

Hardfacing Alloy Selection

There is no standardized method of classifying and specifying the different surfacing weld rods and electrodes. The American Welding Society has issued two specifications, A5.13, "Specifications for Surfacing Weld Rods and Electrodes," and A5.21, "Specifications for Composite Surfacing Weld Rods and Electrodes." There is some overlap between these two specifications and with A5.6 and A5.7, "Copper and Copper Alloy Welding Electrodes and Rods." Many of the hardfacing electrodes commercially available are not covered by these specifications. Filler metal suppliers provide data establishing classes of service and have categorized their products within these classes. Suppliers also provide complete information for using their products for various applications and for different industries, such as quarrying, steel mills, foundries, and so on. This information is extremely valuable and should be consulted.

A good system of classification has been established by the American Society for Metals Committee on Hardfacing. This data is found in the *Metals Handbook*,[8] Section 3, "Hardfacing by Arc Welding." This system has five major groups classed according to alloy content, with subdivisions based on the major alloying elements. These data have been abridged and simplified by Spencer who added the AWS Specifications where they apply[9] (Figure 24-11). Most of these alloys are available as solid bare filler rod in straightened lengths or in coils or covered electrodes. Some of the materials are available as powder for special applications. Following is a brief description of the five major groups, what they contain as alloys, and where they are recommended.

Group 1 is the low-alloy steels that, with few exceptions, contain chromium as the principal alloying element. The subgroup 1A has from 2 to 6% alloy including carbon. These alloys are often used as buildup materials under higher-alloy hardfacing materials. The group 1B is similar except that they have a higher-alloy content ranging from 6 to 12%. Several alloys in the group have higher carbon content exceeding 2%, and include several alloy cast irons. The alloys of group 1 have the greatest impact resistance of all hardfacing alloys except the austenitic manganese steels (group 2D) and have better wear resistance than low or medium carbon steels. They are the least expensive of the alloy surfacing materials and are extremely popular. They are machinable and have a moderate improvement over the wear properties of the base metal to which they are welded. They have a high compressive strength and fair resistance to erosion and scratch abrasion.

Group 2 contains higher alloyed steels. Group 2A has chromium (Cr) as the chief alloying element, with a total alloy content of 12 to 25%.

Many of these alloys also contain molybdenum. Those with over 1.75% carbon are medium-alloy cast irons. Group 2B has molybdenum (Mo) as the principal alloying element but many also contain appreciable amounts of chromium. The hardfacing alloys of groups 2A and 2B are more wear resistant, less shock resistant, and more expensive than those in group 1.

Group	AWS Class	C %	Mn %	Si %	Cr %	Ni %	Mo %	W %	V %	Co %
1A	—	0.10	1.3	0.75	2.0		1.0			
		0.25	0.8	0.50	0.4	0.70	0.6			
		0.20	0.25	0.40	3.25		1.0			
		0.35	1.2	0.10	4.0		0.5			
		0.55	1.0		1.8			2.25		
[illegible]	—	0.70	0.9	0.3	6.5		0.8			
		0.70	1.0	0.7	3.0		4.0			
		0.70	1.2	1.0	5.0		0.5			
		2.2	0.4	0.5	5.0				5.0	
		3.0	0.7	1.0	3.0					
		3.4			4.8				2.4	
[illegible]	—	0.6	0.4	0.7	7.0		0.9	3.5	1.0	
		0.5	2.0	1.0	9.0		1.7			
		3.0	2.5	1.0	12.0		1.5			
		1.0	4.0		12.0					
		3.8			15.0	2.0	8.0			
		3.0			16.0	6.0	8.0			
[illegible]		0.80			4.0		9.0		1.5	
		1.0			0.9		15.3			
		1.4			4.2		9.7			
		3.5			5.0		4.0			
	RFeMoC	3.6					10.0			
	EFe5A	0.85	0.5	0.7	4.0		5.0	6.0	2.0	
	EFe5B	0.70	0.5	0.7	4.0		8.0	2.0	1.0	
	EFe5C	0.40	0.5	0.7	4.0		8.0	2.0	1.0	
[illegible]	EFeMnA	0.80	16.0	0.3	0.4	4.0				
	EFeMnB	0.80	14.0	0.8	0.5		1.0			
		1.2	12.0	0.6		4.8				
3A		2.7	1.0	1.0	26.0					
		3.0			18.0		16.0		1.5	6.0
		3.7	1.0	0.8	28.0					3.0
	EFeCrA1	4.0	6.0	1.7	29.0					
	EFeCrA2	4.0	1.0	1.3	29.0	3.5				
3B	—	2.5			25.0	12.0	8.0			
		4.0		4.5	16.0				0.5	
		4.0		1.0	17.0	6.0			0.5	
		3.4	4.5	0.8	30.0					
3C	—	2.3			16.0	6.0				20.0
		3.6	0.6	1.6	15.5		3.0			23.5
4A	ECoCrA	1.0	2.0	0.5	29.0	3.0	1.0	4.0		Rem.
	ECoCrB	1.3	2.0	1.0	29.0	3.0	1.0	8.0		Rem.
		2.5			32.0		17.0			Rem.
	ECoCrC	2.5	2.0	1.0	30.0	3.0	1.0	12.0		Rem.
		0.3			27.0	2.7	5.0			Rem.
4B	ENiCrA	0.35		3.5	12.0	Rem.				
	ENiCrB	0.40		4.0	15.0	Rem.				
		0.10			16.0	Rem.	17.0	4.5		
	ENiCrC	0.75		4.5	15.0	Rem.				1.0
4C	—	2.5			29.0	39.0		14.0		8.0
		2.5			25.0	15.0	8.0			25.0
		3.7			16.0	4.0	6.5			20.0
5	EWC	Tungsten carbide particles (38 to 60+ % encased in matrix most wear resistant of materials.								
	RWC									

FIGURE 24-11 Typical composition of hardfacing materials.

Groups 2A and 2B are quite strong and have relatively high compressive strengths. They are effective for rebuilding severely worn parts and are used for buildup prior to using higher alloy facing materials. They provide high impact resistance and good abrasion resistance at normal temperatures.

Group 2C contains tungsten and modified high-speed tool steels. They are excellent choices at service temperatures up to 1100 °F (593 °C) and when good resistance coupled with toughness is required. They are not considered as good high abrasion-resistant types but are resistant to hot abrasion up to 1100 °F and exhibit good metal-to-metal wear at elevated temperatures.

Group 2D are the austenitic manganese steels, which contain either nickel or molybdenum as stabilizers. The alloys in group 2D are highly shock resistant but have limited wear resistance unless subjected to work hardening. The total alloy content ranges from 12 to 25%. This group is excellent for metal-to-metal wear and impact when the deposit is work hardened in use. The as-welded deposit hardness is low, from 170 to 230 BHN, but will work harden to 450 to 550 BHN. The deposit may deform under battering but it will not crack. The deposit should not be heated to above 500 °F (260 °C), which would cause embrittlement.

Group 3 contains higher-alloyed compositions ranging from 25 to 50% total alloy. They are all high-chromium alloys and some contain nickel, molybdenum, or both. The carbon can range from slightly under 2% to over 4%. The alloys in this group exhibit better impact, erosion resistance, metal-to-metal wear, and shock resistance than the previous groups. The 3B grouping will withstand elevated temperatures of up to 1000 °F (538 °C). The 3C group is high in cobalt which improves high-temperature properties. The group 3 alloys are more expensive than groups 1 and 2.

The compositions within group 4 are nonferrous alloys—either cobalt base or nickel base with total content of nonferrous metals from 50 to 99%.

The group 4A alloys are the high-cobalt-based alloys with high percentage of chromium. These alloys are used exclusively for applications subjected to a combination of heat, corrosion, erosion, and oxidation. They are considered the most versatile of the hardfacing materials. The alloys with higher carbon are used for applications requiring high hardness and abrasion resistance but when impact is not as important. These alloys are excellent when service temperatures are above 1200 °F (649 °C). They resist oxidation temperatures of up to 1800 °F (982 °C).

The group 4B alloys are the nickel-base alloys, which contain relatively high percentages of chromium. This group of alloys is excellent for metal-to-metal resistance, exhibits good scratch abrasion resistance, and corrosion resistance. They will retain hardness to 1000 °F (538 °C). The alloys with higher carbon content provide higher hardnesses but are more difficult to machine and provide for less toughness. These alloys show good oxidation resistance up to 1750 °F (954 °C).

The group 4C alloys are the chrome–nickel cobalt alloys and all are recommended for elevated temperatures. The high-nickel alloy has excellent resistance to hot impact, abrasion, and corrosion and moderate resistance to wear and deformation at elevated temperatures. The medium-nickel alloy has high-temperature wear resistance and impact resistance. It also provides resistance to erosion, corrosion, and oxidation. The low-nickel alloy is used for moderate high temperatures and provides good edge strength, corrosion resistance, and moderate strength.

The group 5 alloys provide a tungsten carbide weld deposit. This deposit consists of tungsten carbide particles distributed in a metal matrix. The matrix metals may be iron, carbon steel, nickel-base alloys, cobalt-based alloys, and copper-base alloys. The tungsten carbide particles are crushed to mesh sizes varying from 8 to 10 down to 100 and have excellent resistance to abrasion and corrosion, and moderate resistance to impact. The matrix material determines the resistance to corrosion and high-temperature resistance. The finish of the deposit depends on the tungsten carbide particle size. The finer the particles the smoother the finish. The deposits are not machinable and are very difficult to grind.

There is another class of surfacing materials used to provide corrosion or oxidation resistance surfaces which will be covered in Section 24-6. Figure 24-12 shows the hardsurfacing alloy classes just mentioned and provides properties and the welding processes that can be used. The method of finishing, and the application for the different alloy classes is shown. This is generalized information and is presented as a starting point for making the final selection. A welding procedure should be established for the successful hardsurfacing or overlaying operation. The procedure should relate to the particular part being surfaced. It should specify the welding process, the method of application, and the preweld operations. The welding procedure should give the preheat and interpass temperature and any special techniques that should be employed, such as the pattern of hardsurfacing, whether beading or weaving, the interface between adjacent beads, and finally, any postwelding operations such as peening and the method of cooling. When a properly developed procedure is followed the service life of the job will be predictable.

In many cases two separate materials may be required—the buildup alloy, which is used when the part is to be reclaimed or is excessively worn, and the hardfacing alloy. In general, over three layers of hardfacing alloys are not deposited. The hardsurfacing alloys are considerably more expensive than buildup alloys. The hardsurfacing should be replaced when the hardfacing alloy is worn away. When deposit exceeds three layers

Class & No.	Cold Abrasion	Impact	Erosion	Metal-to-Metal Wear	Corrosion	Hot Abrasion	Rockwell Hardness, Layers & Process	Finishing	Applications
1A	F	Ex	No	No	No	No	RC 30 to 40 FCAW, SAW SMAW, 2-3 layers.	Machinable, with carbide tools.	Used as built-up for hardfacing or by itself. Fair-to-good strength, toughness and moderate abrasion resistance;
1B	F	G	F	F	No	No	RC 50-57 2 layers SAW, SMAW, FCAW	Use carbide tools or grind	Hardfacing or heavy duty built-up application involving heavy impact
2A	F to G	F to G	F	F	No	No	RC 50-55 2 layers SMAW & SAW	Use grinding practices	High strength, low crack sensitivity deposits for severe abrasion and compression, moderate to heavy impact, good resistance to erosion and mild corrosion.
2B	Ex	No	Ex	F	No	No	RC 65 Gas	Use grinding practices	Excellent for cold abrasive wear—also for metal to metal wear and mild impact.
2C	F	F	G	F	F	Ex	RC 55 to 60 anneal to RC 30	Machines if softened.	Hardness up to 1100° F (593° C). Good wear resistance and toughness use for tools.
2D	F to G	Ex	F to G	G to Ex	No	F to G	SMAW & Gas	Use grinding practices	Work hardness—build up and hard facing—austenitic manganese, steel
3A	Ex	F to G	G to Ex	F to G	No	No	RC 47 to 62 SMAW, gas	Machine if softened or grind	Holds hardness up to 800° F (427° C) or 1150° F (621° C) depending on alloy, good wear and oxidation resistance. Moderate impact and severe abrasion.
3B	G to Ex	F to G	F to G	G to Ex	F to G	F	RC 35 to 65 SMAW, gas	Use carbide tool or grind	Excellent abrasion resistance and metal to metal wear at moderate temperatures.
3C	Ex	Ex	F	Ex	G	F	RC 45-55 SMAW, gas	Machinable with carbide tools	Good edge strength—use for tools.
4A	V	V	G	G	G	G	RC 35-50 SMAW, gas	Use carbide tools or grind	Very good for metal to metal wear. Good for hot and cold abrasion—depends on specific alloy. Impact varies.
4B	V	V	G	G	G to E	G	RC-30-40 SMAW, gas	Machinable with carbide tools	Best for corrosion for erosion. Also good for metal to metal wear other properties depend on specific alloy.
4C	Ex	G	F	F	G	Ex	SMAW, gas	Use carbide	Excellent wear resistance. Good high temperature properties.
5	Ex	F	G	No	V	V	RC 90-95 SMAW, gas	Use grinding practices	Severe abrasion. Limited to 1200° F (649° C). Moderate resistance to impact.

Ex-Excellent, G-Good, F-Fair, No-do not use, V-Varies

FIGURE 24-12 Hardfacing alloys versus surface conditions.

other problems may be encountered such as cracking, which will influence the service life of the deposit. The other factor to be considered is dilution. This is the diluting of the hardfacing alloy with base metal. Excessive dilution will reduce the effectiveness of the hardfacing material. Excessive penetration and poor tie-in of adjacent beads should be avoided.

A major consideration is the location of finished surface with respect to the worn surface. In many cases, the first layer of surfacing may have sufficient dilution of base metal so that it is unsuitable for the desired service. In this case, the worn surface should be further removed so that there is sufficient room for two layers of surfacing metal, which will provide a better service life. There are other situations in which the part is to be remachined after surfacing. The machining surface should not be at the interface between weld surfacing metal and the base metal. Premachining may be required. This is important when the base metal is of hardenable material.

Preheating, interpass temperature, and cooling of the part being surfaced are important. The factors that apply to welding the base metal in normal fabrication should be followed when overlaying. Preheating is used to minimize distortion, to avoid thermal shock, and to prevent surfacing cracking. The preheat temperature depends on the carbon and the alloy content of the base metal and the mass of the part being surfaced. A soak-type preheat should be used. If it is extremely complex in shape, preheat should be increased. The preheat temperature should be maintained throughout the entire welding operation and should then be allowed to slow cool.

The base metal composition must be known in order to provide proper preheat temperatures.

Welding should be done in the flat position if at all possible. If not possible, the correct electrode and procedure must be specified.

The thickness of the surfacing deposit is extremely important. If the deposit is too thick, problems can be encountered. Hardfacing alloys should be restricted to two layers. The first will include dilution from the base metal, but the second layer should provide the properties expected. Some types of alloys can be used in three layers. Consult the manufacturer's data for the particular product involved.

The technique for buildup should be to within ¼ in. (6 mm) of the final surface. This will then allow two layers of surfacing material to bring the part to final dimension. A weaving technique is recommended instead of stringer bead welding. The pass thickness or layer thickness should not exceed $\frac{3}{16}$ in. (5 mm). The adjacent beads must fair into the previous bead to provide as smooth a surface as possible. There is controversy concerning the pattern of welds that should be made when applying the surfacing deposits. In general, the direction of welding should not be transverse to the load on the part. This can create stress concentrations and may affect service life. In certain types of metal, peening is recommended but this is based on the metal. The manufacturer's instructions should be followed.

Hardfacing by welding is an excellent method of reclaiming parts and will save considerable time and money. It is becoming popular for original equipment manufacturers to hardface wear parts on new equipment to provide better service life of the equipment.

24-6 SURFACING FOR CORROSION RESISTANCE

The corrosion of metals is one of the more expensive factors that cause premature failures of most objects from automobile bodies to chemical plant equipment to ship hulls. Corrosion can be prevented or at least substantially reduced so that metal parts will have a longer life. One of the best ways to reduce corrosion is to protect the metal with an overlay or surface of a material less susceptible to corrosion in a specific environment. Galvanized steel and clad metals with nonferrous facings have long been used to reduce corrosion.

The deterioration of metal surfaces is caused by the combination of factors, such as corrosion and oxidation, corrosion and erosion, or cavitation. Before repairing corroded or deteriorated surfaces, it is necessary to analyze the reason for the deterioration. These factors should be considered in selecting a material for overlays for specific types of service. After the surfacing material is selected, it is important to determine how it is to be applied. Different methods and techniques can be used to apply the corrosion resistance surface. This can be done by applying small pieces of corrosion-resistant metal by plug and seam welding them to the inside of the tank. The other method is to use the corrosion-resistant material as filler metal and deposit the surfacing metal directly on the corroded areas.

When attaching liner plates or sheets to carbon mild steel, the problems of welding dissimilar metals must be considered. This involves the metallurgical requirements of the clad material and the compatibility of the two materials. When the solid solubility of one element to be dissolved in another is exceeded, cracking may occur. In addition, the effects of elements such as sulfur and phosphorus from dilution can be a source of trouble. The welding technique and procedure involving the selection of filler metals, coatings, fluxes, and so on, must be considered, as with any dissimilar welding operation. The same factors apply when the material is being applied as a weld surfacing.

There are a number of alloys that are used for overlays or clads for corrosion and oxidation resistance. These are usually standardized compositions commonly used by themselves for the same requirements. These are summarized as follows:

The copper-base alloys are used for certain corrosion requirements. The copper–silicon alloys and the copper tin alloys are used for certain corrosion-resistance requirements.

The austenitic stainless steels, which include the standard alloy types 308, 309, 310, 316, and 347, are all used for corrosion-resistant surfaces. These alloys exhibit moderate resistance to high-stress abrasion and have excellent oxidation resistance and impact properties.

The nickel-base alloys are also used. This includes 100% nickel, the Monel (67% Ni–30% Cu) and Inconel (72% Ni–7% Fe–16%CR). These alloys are frequently used as overlays on carbon and low-alloy steels for cladding of tanks and vessels.

The high-cobalt chromium alloys are used for specific overlays when corrosion is a major problem. These are used quite often in refineries where corrosive materials are pumped and stored at high pressure and high temperatures. These alloys can be applied in several ways: as a powder applied by the plasma process, as a cold wire, or by covered electrodes with the shielded metal arc welding process. The selection of the overlay is based entirely on the requirements of the materials to which the product is exposed. The selection must be based on normal metallurgical factors.

A unique application of weld overlay is to repair digesters used in pulp and paper mills. Digesters are pressure vessels ranging in height from 25 to 50 ft and in diameter from 8 to 12 ft. They are used for the first chemical processing step of converting wood chips into pulp for paper with the sulfate or kraft process. The mixture of wood chips and alkaline liquor is under pressure and operates at a relatively high temperature.

The internal surfaces of digesters corrode at a high rate at the surface of the liquor and gradually deteriorate until they become so thin that pressures and temperatures must be reduced for safety.

Welding has been employed to repair the pitted or corroded areas and to rebuild wall thickness to original dimension. Originally, carbon steel weld metal was used. It was found that stainless steel provides a surface that is less subject to the corrosive action. Tests revealed that stainless overlay outlasts the original carbon steel many times.

Gas metal arc welding has been used for this overlaying operation. The automatic machine will deposit weld metal in horizontal beads on the vertical inside circumference of the tank. The welding heads are mounted on a boom that rotates about the centerline of the tank and deposits metal as it revolves inside the tank. It is possible to utilize two or even three automatic heads that automatically travel around the inside circumference of the tank. This work is done starting at the bottom and moves upward as it revolves. The most popular procedure uses type 316 or 310 stainless alloy in the 0.035-in.-diameter electrode wire with argon for shielding.

In normal applications the inside diameter of the digester is prepared for welding by grit blasting the entire surface to be welded. This is followed by an acid wash and water rinse. The welding operation, once it is begun, is continuous, to eliminate any voids in the surface. Each pass must fair smoothly into the previous one and the depth of the surface should be from $\frac{1}{8}$ to $\frac{3}{16}$ in. thick.

This technique is sometimes used for new digesters to reduce the rate of corrosion and the length of time between maintenance repair work. Penetration must be closely controlled so that dilution will not appreciably lower the alloy content of the deposit.

Other procedures for accomplishing an overlay on the inside diameter of smaller tanks are done by rotating the tank and doing the welding in the flat position. The welding is done by the submerged arc process using one or more electrode wires. Some situations use the strip overlay method. The submerged arc welding process increases the speed of making the overlay. In some cases the GTAW or plasma hot wire process is used. Use the process that is most appropriate for the position and the job to be done.

Normally, single layers are used; however, for applications such as pump linings and high-wear areas, a second layer of surfacing is applied. The second layer can be made with an electrode of lower alloy content since the dilution factor is drastically reduced.

Figure 24-13 shows the submerged arc strip over-

FIGURE 24-13 Submerged arc strip overlay.

lay method being used to surface an extremely large area. This is an automatic method where the work is moving under the welding head. Welding procedures must be developed and qualified for the applications.

24-7 OTHER SURFACING APPLICATIONS

There are other surfacing requirements which are best done by welding.

One popular use of surfacing is the overlaying of metal parts with bronze to provide wearing surfaces for metal-to-metal contact. This includes guides and ways for reciprocating and sliding motion. In order to avoid making a part completely of brass or bronze it is possible that it can be made of steel and then overlaid with a bronze. The copper-base alloys provide a relatively soft deposit for metal-to-metal wear. The AWS Class ECuA1 types, which are the aluminum bronzes, are well suited for overlay for bearing surfaces. The different classes such as ECuA1 A-2, B, C, D, and E can all be used. The hardness is greater with the higher suffix letters.

Aluminum bronze overlays can be used for plungers in pumps, rams in extrusion presses, and for rings on hydraulic rams. They will wear faster than the hardened steel with which they make contact. It is advantageous to concentrate the wear on the bronze which can be replaced rather than cause wear on the inside diameter of a hardened steel cylinder.

The aluminum bronzes can also be used for repair welding of worn bronze bearings used in heavy slow moving machinery, and for overlaying worn cast iron gears and sheaves. By overlaying with bronze and remachining, the part can be made better than new.

Overlay of bronze is sometimes used for decorative purposes, particularly for architectural metal applications. By judicious use of the bronze and stainless steel the color contrast can be made very attractive.

Another use for bronze surfacing is for projectiles where a brass overlay is welded around the projectile. This causes it to fit the rifling of the gun barrel tightly to avoid loss of pressure and also to give the desired spin to the projectile.

The use of weld surfacing can be extended to provide safety surfaces. When metal flooring becomes smooth from wear it is possible to run stringer beads on the smooth surface to produce a rougher surface. The weld surface will be safer and eliminate slipping. This is used on treads of metal steps, walkways, and other places where smooth metal surfaces can be hazardous. Undoubtedly, there are other applications for surfacing and overlays since it is an ideal method to utilize less expensive materials and provide specialized materials for specific surfaces.

QUESTIONS

24-1. What are the four areas of interest when making a failure analysis?

24-2. What is a monolithic structure? Is a weldment a monolithic structure?

24-3. What are the four points of a failure analysis?

24-4. When should repair welding *not* be performed?

24-5. Approval of a repair procedure is required on what type of products?

24-6. Why is it wise to prepare a written procedure for repair welds?

24-7. List the factors involved in preparation for repair welding.

24-8. List the factors involved in repair welding.

24-9. List the factors involved in repair postweld treatment.

24-10. Explain rebuilding, overlaying, and surfacing. How do they differ?

24-11. What is the best process to use to rebuild small shafts?

24-12. Define and give an example of impact wear.

24-13. Define and give an example of abrasion wear. How is it different from erosion?

24-14. Define and give an example of corrosion wear. How is it different from oxidation?

24-15. What is the basis for selecting hardfacing alloys?

24-16. What is a buildup surfacing material? Where is it used?

24-17. What is corrosion-resistant weld-overlay cladding? Where is it used?

24-18. What is the advantage of stainless steel cladding over carbon steel?

24-19. Why are wear parts surfaced with bronze or brass?

24-20. How is weld surfacing used to provide a safety surface?

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25

Pipe and Tube Welding

OUTLINE

25-1 TUBULAR PRODUCTS

Tubular products, known as pipe or tubing, are hollow items, normally circular, used for transmitting gases or liquids, or for structural, mechanical, or decorative functions. They can range in diameter from the smallest to the largest and with wall thicknesses from very thin to relatively heavy. Tubular products can be manufactured as seamless or welded. Welded tubular products are the most popular and are the only one considered here. There are many different ways of classifying pipe and tubing, but are usually based on shape and intended use. General classifications are as follows:

1. *Standard pipe:* used for transmission of low-pressure air, steam, other gases, water, oil, and/or other fluids. Used primarily in buildings, sprinkler systems, irrigation systems, and in machinery.
2. *Line pipe:* used for the transportation of gas, oil, water, and so on, in cross-country pipelines and for utility distribution systems.
3. *Oil country goods:* tubular products used by the oil and gas industries with three subdivisions: casings for well walls, tubing used within the casings, and drill pipe used to carry rotary drilling tools.

4. *Pressure tubing:* used to transmit fluids or gases at elevated temperatures or pressures or both.
5. *Mechanical tubing:* used to manufacture industrial, construction, and agriculture equipment.
6. *Structural pipe and tube:* used for structural or load-bearing purposes, for architectural or structural purposes, and can be of different shapes.
7. *Thin-wall tubing:* used for instrument tubing, aircraft control tubing, air conditioning, and miscellaneous applications; can be of different sizes and of stainless steels and nonferrous metals.

Each classification can be made of different materials. Standard pipe is normally made of carbon steel. It may be uncoated, galvanized, or plastic coated, and is made in different wall thicknesses, known as standard, extra-strong, double-extra strong, and others. Wall thickness may be indicated by schedule number (Figure 25-1). Schedule 40 is standard-weight pipe.

Line pipe is made of carbon steel or of low-alloy high-strength steel. They are made of weldable steels since line pipe is normally joined by welding. Line pipe is made to API specifications.

Oil country goods are made of carbon steel and alloy steels, and some items are made of extremely high-alloy high-strength materials.

Pressure tubing, which is made to exact dimensions of outside diameter and wall thickness, is made of carbon steels, alloy steels, creep-resisting steels, heat-resisting steels, and stainless steels of different types.

Structural steel pipe and tube is made of low-carbon weldable steels. The analysis of the steel used for making the pipe is normally specified by the producer, or by specifications for the material.

Thin-wall tubing is made of low-alloy steels and stainless steels. Stainless steel tubing is available in almost any alloy of stainless available. In addition to steels, tubing is available in aluminum, copper, titanium, and nickel alloys.

The dimensions used for pipe and tubing depend on the product classification and the country of origin. See standard pipe sizes mentioned above and metric sizes shown in Figure 25-2.

In specifying pipe and tubing, it is necessary to provide exact dimensions and the material classification or composition in order to obtain the type requested.

Methods for Manufacturing

Welded tubing is preferred over seamless tubing since it has more uniform wall thickness and is normally less expensive. The following welding processes are used to make pipe and tubing:

1. The continuous butt welding process
2. The resistance welding processes
3. The arc welding processes
4. The high-energy beam (electron and laser) processes

There are two types of weld joints employed. The most common is the straight longitudinal joint from end to end of pipe, used for all sizes from smallest to largest. The spiral joint, which is used for medium- and larger-sized tubular products, is usually welded with the submerged arc welding processes.

The continuous mill for making tubular products, when the weld joint is longitudinal, is similar for all of the welding processes.[1] A continuous mill (Figure 25-3) consists of the following:

1. The coil of strip or skelp
2. The splicing operation for the skelp
3. Strip flattening and trimming station (optional)
4. Multiple forming rolls, including closing rolls
5. Welding station, including the squeeze or pressure rolls
6. Sizing rolls, or die
7. Cut off operation

The number and size of rolls, number of stations, and so on, will vary depending on the manufacture of the mill and the size and type of tubular products being produced.

The welding station produces a high-quality weld with full penetration, minimum root and face reinforcement, and minimum bead widths. The weld must be smooth, uniform, and clean without cracks and without undercutting and the reinforcement of the weld should not exceed 10% of the wall thickness.

The so-called butt welding process, commonly called the CW (continuous welding) process, is the oldest welding process for welding pipe. It is actually forge welding in which the flat stock, known as skelp, is formed into a tubular shape while very hot and pulled through a die. This causes the abutting edges to come together under very high pressure and high temperatures in a continuous welding mill, to make a forge weld. This process is used to manufacture standard pipe of ⅛ to 4 in. nominal diameter at high rate of speed on a continuous butt-welded pipe mill.

There are three electric resistance welding processes employed for continuous mill welding. The choice of the welding process variation depends on the diameter of the tubular product, the wall thickness, and the production rate. In all three methods the power for welding is provided either by low-frequency current through revolving electrode wheels, or by radio-frequency current through sliding contacts or induction coils.

Gas tungsten arc welding is popular for thin-wall stainless tubing and tubing made of nonferrous alloys. As wall thickness increases, more torches may be used

FIGURE 25-1 Standard pipe size and wall thickness.

Nominal Pipe Size (in.)	Outside Dia.	Nominal Wall Thickness For: Sched. 5	Sched. 10	Sched. 20	Sched. 30	Standard	Sched. 40	Sched. 60	Extra Strong	Sched. 80	Sched. 100	Sched. 120	Sched. 140	Sched. 160	XX Strong
⅛	0.405	—	0.049	—	—	0.068	0.068	—	0.095	0.095	—	—	—	—	—
¼	0.540	—	0.065	—	—	0.088	0.088	—	0.119	0.119	—	—	—	—	—
⅜	0.675	—	0.065	—	—	0.091	0.091	—	0.126	0.126	—	—	—	—	—
½	0.840	—	0.083	—	—	0.109	0.109	—	0.147	0.147	—	—	—	0.187	0.294
¾	1.050	0.065	0.083	—	—	0.113	0.113	—	0.154	0.154	—	—	—	0.218	0.308
1	1.315	0.065	0.109	—	—	0.133	0.133	—	0.179	0.179	—	—	—	0.250	0.358
1¼	1.660	0.065	0.109	—	—	0.140	0.140	—	0.191	0.191	—	—	—	0.250	0.382
1½	1.900	0.065	0.109	—	—	0.145	0.145	—	0.200	0.200	—	—	—	0.281	0.400
2	2.375	0.065	0.109	—	—	0.154	0.154	—	0.218	0.218	—	—	—	0.343	0.436
2½	2.875	0.083	0.120	—	—	0.203	0.203	—	0.276	0.276	—	—	—	0.375	0.552
3	3.5	0.083	0.120	—	—	0.216	0.216	—	0.300	0.300	—	—	—	0.438	0.600
3½	4.0	0.083	0.120	—	—	0.226	0.226	—	0.318	0.318	—	—	—	—	—
4	4.5	0.083	0.120	—	—	0.237	0.237	—	0.337	0.337	—	0.438	—	0.531	0.674
5	5.563	0.109	0.134	—	—	0.258	0.258	—	0.375	0.375	—	0.500	—	0.625	0.750
6	6.625	0.109	0.134	—	—	0.280	0.280	—	0.432	0.432	—	0.562	—	0.718	0.864
8	8.625	0.109	0.148	0.250	0.277	0.322	0.322	0.406	0.500	0.500	0.593	0.718	0.812	0.906	0.875
10	10.75	0.134	0.165	0.250	0.307	0.365	0.365	0.500	0.500	0.593	0.718	0.843	1.000	1.125	—
12	12.75	0.156	0.180	0.250	0.330	0.375	0.406	0.562	0.500	0.687	0.843	1.000	1.125	1.312	—
14	14.0	—	0.250	0.312	0.375	0.375	0.438	0.593	0.500	0.750	0.937	1.093	1.250	1.406	—
16	16.0	—	0.250	0.312	0.375	0.375	0.500	0.656	0.500	0.843	1.031	1.218	1.438	1.593	—
18	18.0	—	0.250	0.312	0.438	0.375	0.562	0.750	0.500	0.937	1.156	1.375	1.562	1.781	—
20	20.0	—	0.250	0.375	0.500	0.375	0.593	0.812	0.500	1.031	1.281	1.500	1.750	1.968	—
22	22.0	—	0.250	—	—	0.375	—	—	0.500	—	—	—	—	—	—
24	24.0	—	0.250	0.375	0.562	0.375	0.687	0.968	0.500	1.218	1.531	1.812	2.062	2.343	—
26	26.0	—	—	—	—	0.375	—	—	0.500	—	—	—	—	—	—
30	30.0	—	0.312	0.500	0.625	0.375	—	—	0.500	—	—	—	—	—	—
34	34.0	—	—	—	—	0.375	—	—	0.500	—	—	—	—	—	—
36	36.0	—	—	—	—	0.375	—	—	0.500	—	—	—	—	—	—
42	42.0	—	—	—	—	0.375	—	—	0.500	—	—	—	—	—	—

Nominal Pipe Size		Schedule	Outside Diameter		Wall Thickness	
in.	mm	Number	in.	mm	in.	mm
⅛	3	10	0.405	10.3	0.049	1.2
		40			0.068	1.7
		80			0.095	2.4
¼	6	10	0.540	13.7	0.065	1.7
		40			0.088	2.2
		80			0.119	3.0
[illegible]	10	10	0.675	17.1	0.065	1.7
		40			0.091	2.3
		80			0.126	3.2
[illegible]	13	5	0.840	21.3	0.065	1.7
		10			0.083	2.1
		40			0.109	2.8
		80			0.147	3.7
[illegible]	19	5	1.050	26.7	0.065	1.7
		10			0.083	2.1
		40			0.113	2.9
		80			0.154	3.9
1	25	5	1.315	33.4	0.065	1.7
		10			0.109	2.8
		40			0.133	3.4
		80			0.179	4.5
1¼	32	5	1.660	42.2	0.065	1.7
		10			0.109	2.8
		40			0.140	3.6
		80			0.191	4.9
1½	38	5	1.900	48.3	0.065	1.7
		10			0.109	2.8
		40			0.145	3.7
		80			0.200	5.1

Nominal Pipe Size		Schedule	Outside Diameter		Wall Thickness	
in.	mm	Number	in.	mm	in.	mm
2	51	5	2.375	60.3	0.065	1.7
		10			0.109	2.8
		40			0.154	3.9
		80			0.218	5.5
2½	64	5	2.875	73.0	0.083	2.1
		10			0.120	3.0
		40			0.203	5.2
3	76	5	3.500	88.9	0.083	2.1
		10			0.120	3.0
		40			0.216	5.5
3½	89	5	4.000	101.6	0.083	2.1
		10			0.120	3.0
		40			0.226	5.7
4	102	5	4.500	114.3	0.083	2.1
		10			0.120	3.0
		40			0.237	6.0
6	152	5	6.625	168.3	0.109	2.8
		10			0.134	3.4
8	203	5	8.625	219.1	0.109	2.8
		10			0.148	3.8
10	254	5	10.750	273.1	0.134	3.4
		10			0.165	4.2
12	305	5	12.750	323.9	0.156	4.0
		10			0.180	4.8
14	356	5	14.000	355.6	0.156	4.0
		10			0.188	4.8

FIGURE 25-2 Metric pipe size and wall thickness.

FIGURE 25-3 Continuous mill for making tubular products.

Wall Thickness		Travel Speed		Current (A) DCEN	Arc Voltage (V)	Shield Gas Type	Joint Detail Type
in.	mm	in./min	mm/min				
0.078	1.98	12	305	180	10	Argon	Square butt
0.078	1.98	20	508	200	12	Argon + 5% H_2	Square butt
0.109	2.77	16	406	220	10	Argon	Square butt
0.126	3.18	10	254	230	11	Argon	Square butt
0.154	3.91	12	305	245	12	95 argon + 5% H_2	60° V
0.216	5.48	8	205	260	13	95 argon + 5% H_2	60° V
0.226	5.74	7	178	240	13	95 argon + 5% H_2	60° V
0.237	6.02	6	167	280	13	95 argon + 5% H_2	60° V

FIGURE 25-4 **Welding schedule for GTAW welding stainless steel tubing.**

and filler wire may be employed. Plasma arc welding is finding increased use for stainless steel tube mills. Gas metal arc welding is often employed where thickness is greater and filler metal is required. For thick-wall pipe made in short lengths, flux-cored arc welding or submerged arc welding can be used. These processes are used for making spiral joint pipe.

The gas tungsten arc welding process produces high-quality welds in tube mills in square groove welds from 0.020 in. (0.5 mm) to 0.118 in. (3 mm) thick without the addition of filler wire. The wall thickness of the tubing and the metal composition greatly influence the welding parameters. Most procedure tables for mechanized welding relate to average conditions. Tubular product mills use welding data that are modified for maximum travel speed. The welding parameters must be analyzed and each adjusted to provide for maximum travel speed.

The primary variables are travel speed, welding current, and arc voltage. This is the heat input into the weld. The secondary adjustable variables include the torch travel angle and the arc direction when a magnetic arc deflecting system is used. The distinct level variables include the electrode size, type and point geometry, the composition of the shielding gas, and trailing gas shield if used. The use of more than one torch and their spacing, and the use of oscillation either mechanical or magnetic.

The fixed conditions include thickness and composition of the metal. Increasing productivity means increasing the speed of the tube, which can be done by increasing the energy employed in making the weld. A combination of improvements can increase the welding speed of the tube mill. Revise the welding procedure by examining each variable and adjusting them independently until the right combination has been obtained. Figure 25-4 gives parameters for single-arc gas tungsten arc welding for stainless steel of the wall thicknesses shown.

Adjust the primary variables, which relate to heat input. Increase the welding current; as the welding current increases, the travel speed must also increase, to avoid burn-through. The travel speed must be continuously adjustable so that it can be changed as the current is increased. The top limit of current seems to be approximately 250 to 300 A.

Arc voltage is a more complex variable which relates to arc length; it can be varied between narrow limits. The minimum arc length should not be less than one diameter of the electrode. The maximum arc length should not be more than twice the diameter of the elecrode. The torch should be adjustable so that the arc length can be varied easily. Many GTAW mills use automatic arc length control (ALC or AVC), which allows setting the torch to a specific arc voltage.

Travel speed must be increased. The practical maximum speed, approximately 1 m (39 in.) per minute is limited by the quality of the weld. As travel speed increases beyond this rate, undercutting will occur. The weld bead may be high and crowned, and after there will be a depression in the center of the bead which introduces a notch and reduces the cross section along the weld centerline (Figure 25-5).

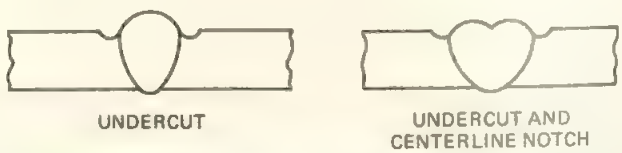


FIGURE 25-5 **Undesirable weld cross section.**

These defects occur because of a dragging arc (Figure 25-6). This makes the arc longer as travel speed increases. As the arc length increases it flares, is less concentrated, does less work, and has a higher voltage. Giving the torch a lead angle overcomes the lagging arc, reduces the arc length, and generally allows travel speed to be increased without undercutting. A push angle of up to 20° will move the undercutting occurrence to a higher speed and tends to flatten the weld bead. This can also be accomplished by a magnetic arc deflection system, which corrects for the arc lag and reduces arc length. This system is adjusted to cause the arc to lead, which preheats the weld area and allows higher travel speeds before undercutting occurs. The torch must be adjustable across

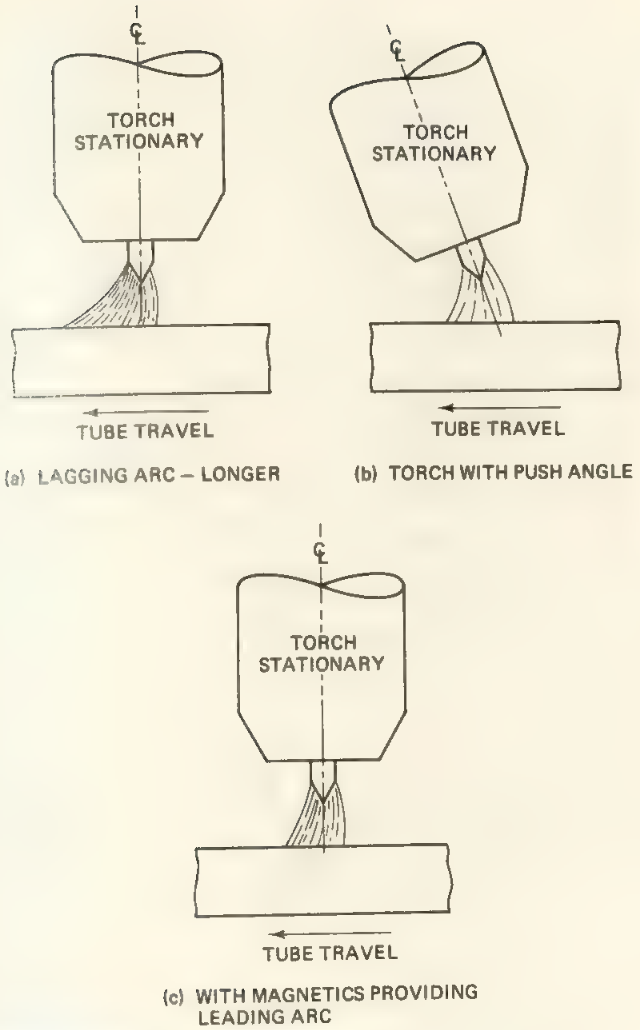


FIGURE 25-6 Arc length factors.

the joint so that it is always located on the center of the seam.

The optimum arc length is approximately 1½ times the electrode diameter, which provides optimum arc voltage for tube welding. The torch angle adjustment is required for the best welding conditions.

Another way to increase the heat input in the arc is to use a shielding gas that provides a higher arc voltage at the same arc length.

Helium provides more heat in the arc, hence travel speed can be increased. Increased production must be related to the higher cost and greater flow rate of helium gas. A mixture of 50:50 argon/helium can be used to reduce gas cost. Another way to increase the heat of the arc is to use hydrogen in the argon shielding gas. Up to 10% hydrogen can be used for welding nickel and nickel alloys and some stainless steels. Hydrogen mixtures should not be used for welding carbon and low-alloy steels.

The use of helium or hydrogen mixtures will increase travel speed up to 50%. Special nozzles are required to shield the longer molten weld pool. Heavy-duty, water-cooled, automatic torches with adjusting rack should be used. The torch rating should be at least 50% greater than the welding current, since tube mill operation is highly demanding.

The tungsten electrode for tube mill use must be selected for heavy duty. For welding ferrous metals, direct-current electrode negative is used. The 2% thoria type (EWTh2) should be used. The ground finish should be specified since this improves heat transfer and increases electrode life and time between regrinding the point. The size of the electrode should be the largest for the welding current to be used. The electrode should be precision ground to a point of 30° included angle, but the end of the point should be flattened.

The use of an additional GTAW torch ahead of the welding arc will allow increased speed since more energy is being put into the material to preheat it. The use of an additional torch following the welding torch will reduce the undercut problem. The use of three torches will increase tube travel speed by up to 100% while producing a good-quality weld joint. The leading (preheat) torch should operate at about 50% of the current of the welding torch. The trailing torch will operate at about 33% of the welding torch. The spacing between the torches should be the minimum.

The plasma arc welding keyhole process can be used in place of the gas tungsten arc to increase the production rate. Speed increase of from 33% to 100% is possible with the greatest improvement on thicker metal. Increased production is due to the higher temperature plasma and the constricted stiffer arc which improves heat transfer to the work. The welding schedule shown in Figure 25-7 shows the productivity improvement.

Wall Thickness		Travel Speed		Current Amperes DCEN	Orifice Size		Gas Shield and Plasma Type
in.	mm	(in./min)	mm/min		in.	mm	
0.062	1.57	14	355	65	0.081	2.05	A + 5% H_2
0.078	1.98	14	355	70	0.081	2.05	A + 5% H_2
0.093	2.36	12	305	85	0.081	2.05	A
0.109	2.77	16	406	85	0.081	2.05	A + 5% H_2
0.126	3.18	10	254	100	0.081	2.05	A + 5% H_2
0.154	3.91	16	406	100	0.081	2.05	A + 5% H_2
0.187	4.75	7	178	100	0.081	2.05	A + 5% H_2

FIGURE 25-7 Welding schedule for plasma arc welding stainless steel tubing.

Analysis and adjustment of all variables would be similar to that described for Gas Tungsten Arc welding.

In submerged arc, gas metal or flux cored arc welding applications multiple torches can be used. With submerged arc using ac three torches are often used.

Electron beam and laser beam welding processes are both used for welding speciality type tubular products.

25-2 PIPE AND TUBE WELDING

In the United States approximately 10% of the steel produced is made into tubular products, essentially pipe. Except for the small sizes, the majority of pipe is installed by welding.

The piping industry is roughly divided into three major categories:

- Pressure or power piping
- Transmission and distribution piping
- Noncritical piping

The welding of pressure piping used in thermal and nuclear power stations, refineries, chemical plants, on ships, and so on, is done in accordance with the ASME code for pressure piping.(2) All of the ASME piping codes of B31 are shown in Figure 25-8. The pipe employed normally has a medium to thick wall thickness in medium to large sizes. Welding procedures, qualifications, and so on, are largely in accordance with Section IX of the ASME pressure vessel code.(3)

Transmission and distribution pipelines transmit gas and petroleum products from the producing fields to the consumers. Welding this type of pipe utilizes special techniques and procedures, and is governed by API Standard 1104.(4) This specification is in general agreement with B31.8, "Gas Transmission and Distribution Piping Systems." The pipe employed is usually of medium to high strength and has relatively thin walls in medium to large diameters. Distribution piping is normally carbon steel standard-size pipe of smaller diameter.

The noncritical piping field includes many different pipes, ranging from domestic hot water supply systems through sprinkler systems, sanitary systems, gas and air lines, and many other applications. Welding has not been universally adopted in this field. Screw-thread connections, soldered copper tubing, and plastic pipe are used for certain applications. The steel pipe is usually standard wall thicknesses in the small and medium sizes. Qualification tests may not be required, although qualified welders and qualified procedures are often used.

Welding pipe and tubular products is normally done in accordance with established written procedures. There are literally thousands of welding procedures in existence based on different processes, codes or specifications, piping materials, and applications. Pipe welds and procedures that will meet the requirements of one specification or code may or may not meet the requirements of others. The specific code involved must be consulted. Welding procedures are designed based on the pipe material, pipe diameter, and wall thickness. Welding position depends on the job and the code, but the procedure must indicate the welding process and progression of travel. The method of application depends on the process and equipment available. The filler metal is selected based on the composition of the pipe material and the quality requirement. A listing of pipe welding procedure schedules is given in Figure 25-9. This list is based on the pipe or tubing size, which is categorized as small [4 in. (100 mm) and smaller], medium [4 in. (100 mm) to 12 in. (300 mm)], and large [12 in. (300 mm) and larger]. The wall thickness is categorized as thin (less than standard), standard (Schedule 40), and heavier (greater than standard). This is followed by the welding position, the welding process, and the method of application. In some cases, combinations of welding processes and methods of application are used.

With these data, welding procedures can be designed to meet the job requirements based on the specification involved. Welding procedure specifications must be qualified to meet the code requirements.

Joint Design

The joint designs for pipe welding have been fairly well standardized and are shown in Figure 25-10. For thinner-wall pipe the joint design is the square groove weld. As thickness increases, a single-V-type joint is used. The included angle of the V groove has been standardized at 60 and 75°. The 75° included angle is more common in pressure piping, and the 60° included angle is common in cross-country transmission-line piping. The root face and root opening are approximately the same. As the wall thickness increases, the joint design will change so that less weld metal will be required. This means that the included angle changes to a narrower angle partially up the joint. These types of joint designs are more commonly used in power plant piping, where heavy wall thickness pipe is used. Other variations in joint design depend on the composition of the pipe. Some automatic procedures require special joint designs. For aluminum pipe special

FIGURE 25-8 ASME code for pressure piping.

B31.1	Power piping
B31.2	Fuel gas piping
B31.3	Chemical plant and petroleum refinery piping
B31.4	Liquid petroleum transportation piping systems
B31.5	Refrigeration piping
B31.8	Gas transmission and distribution piping systems
B31.9	Building services piping
B31.11	Slurry pipelines

Tube & Pipe Diameter & Wall Thickness	Welding Position	Welding Process	Method of Applying
Small tubing-thin wall	All position	GTAW	MA
Small tubing-thin wall	All position	PAW	MA
Small tubing-thin wall	All position	GTAW-No FM	AU
Small pipe-std. wall	All position	OFG	MA
Small pipe-std. wall	All position	GTAW-with FM	AU
Small to medium-std. wall	All position	GMAW	SA
Small to medium-std. wall	All position	SMAW	MA
Medium-std. & heavy wall	All position	Comb. GTAW & SMAW	MA
Medium & large-thin & std.	All downhill	SMAW	MA
Medium & large-thin & std.	All up or down	GMAW	SA
Medium & large-thin & std.	All up or down	FCAW	SA
Medium & large-all wall	All uphill	SMAW	MA
Medium & large-all wall	Flat roll (1G)	SAW	AU
Medium & large-all wall	Flat roll (1G)	Comb. GMAW & SAW	SA or AU & AU
Medium & large-all wall	Flat roll (1G)	Comb. GMAW & FCAW	SA or AU & AU
Small, medium & large-std. to thick	All position	FCAW	SA
Small, medium & large-std. to thick	All position	Comb. GTAW & FCAW	MA & SA
Small, medium & large-std. to thick	All position	Comb. GTAW & GMAW	MA & SA

FIGURE 25-9 Pipe welding procedure schedules.

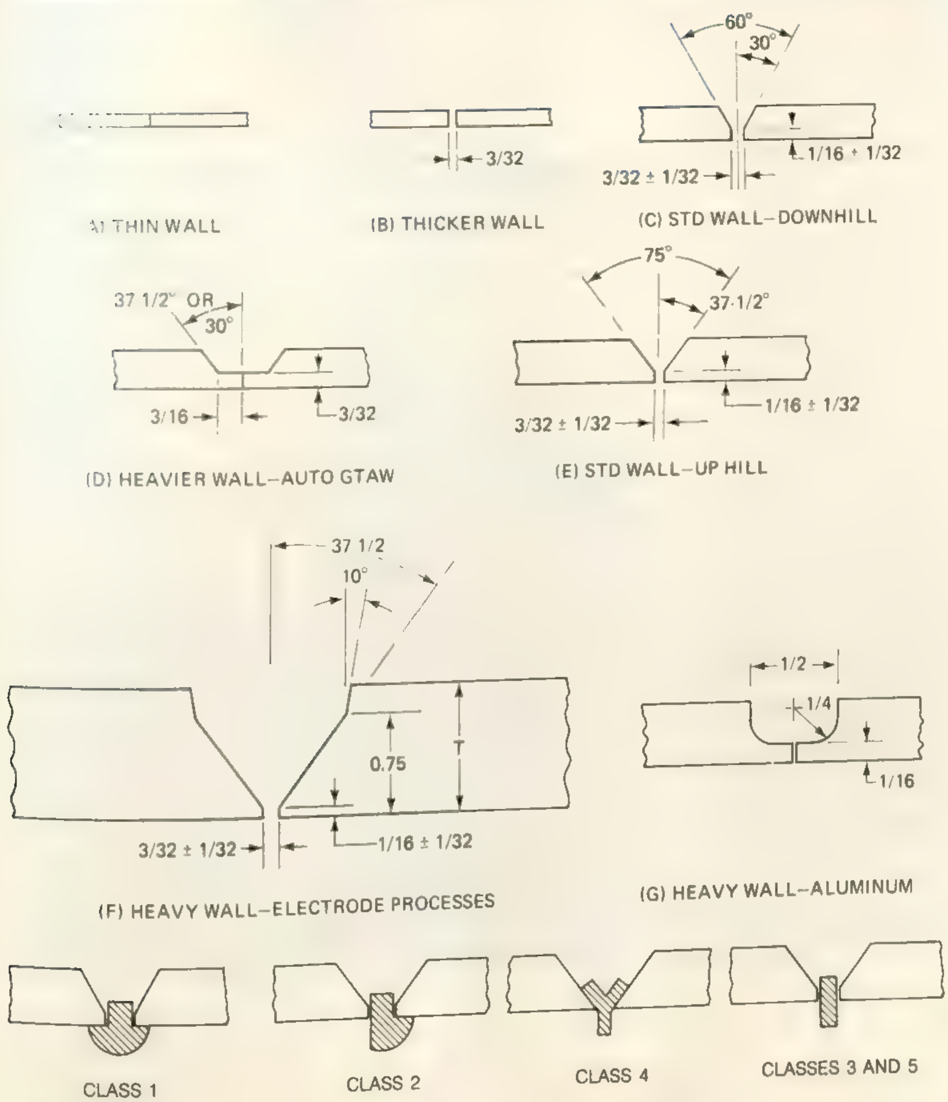


FIGURE 25-10 Pipe welding joint designs.

joint details have been developed, and these are normally associated with combination process procedures. This allows a root weld to be made in much the same manner as the weld on thin-wall tubing.

The rectangular backing ring is rarely used when fluids are transmitted through the piping system. It may be used for structural applications in which pipe and tubular members are used to transmit loads rather than materials. Consumable insert rings are often used for critical piping. In these situations the GTAW process is used for the root pass and the rings are fused into the root of the joint. A variety of designs of insert rings are used. Socket joints and bell and spigot joints which utilize fillets are sometimes used, but they are becoming less popular. Internal gas purging is used for critical pipe work. Special dams of soluble paper or balloons are used to contain the purge gas in the area of the pipe joint. This is most often used with GTAW.

Joint Alignment and Fitup

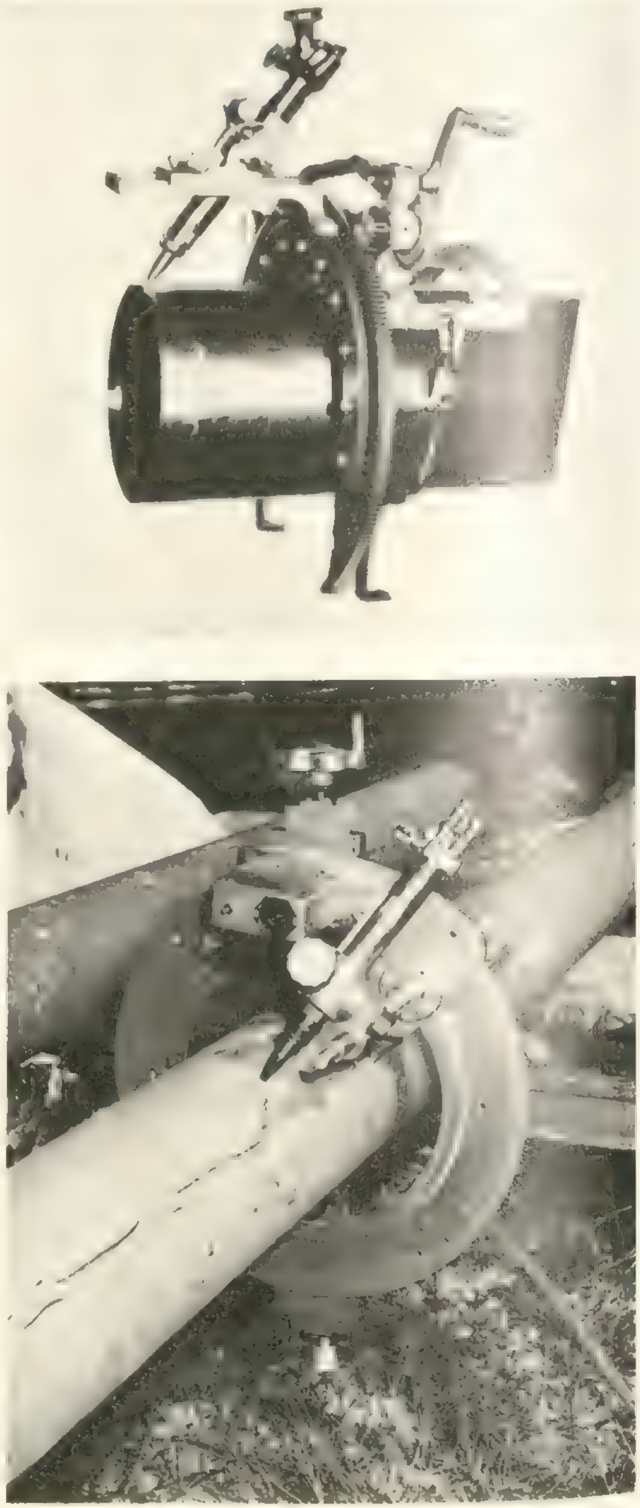
The most important factor in obtaining a high-quality pipe joint is to make sure that the fitup of the joint prior to welding is perfect. It must be in accordance with the joint detail and uniform throughout the circumference of the pipe joint. This is relatively difficult to obtain because pipe is not always exactly round and the diameter may vary within limits of the pipe size. Tubing is made to closer size tolerances and is easier to fit up. The nonroundness or ovality of pipe presents a major welding problem. This is particularly true with larger-diameter pipe.

The most common method of preparing joints for welding is by oxygen flame cutting. Mechanized torches that revolve around the pipe are used. Preparation equipment of this type is shown in Figure 25-11. Automatic and computer-controlled cutting machines are used in the shop. Mechanical cutters are also used to make a uniform joint preparation on pipe. End preparation is prepared at the steel mill on each length of pipe. Forged fittings have the joint preparation prepared at the manufacturer's plant. Special bevels are prepared by mechanical means as a part of some automatic welding machines.

Fitting the pipe is the most difficult part of piping installations. For small assemblies this is relatively easy and much of this work is done in pipe-fabricating shops. Setup and welding subassemblies of different kinds of fittings and pipe sections are welded there under ideal conditions. A typical shop fabrication welded with semiautomatic equipment is shown in Figure 25-12. These assemblies are then transported to the erection site for field welding. Assembly in the field is usually more difficult since dimensional variations are more difficult to control.

A variety of alignment devices are used for pipe installations. For small-diameter pipe, external-type clamps are normally employed. Figure 25-13 shows an assortment of these. Some of these clamps have sufficient force to re-form the pipe into a perfect circle to facilitate fitup. This is possible on the thin-wall pipe but becomes increasingly difficult as the pipe wall thickness increases.

FIGURE 25-11 Preparation of bevels on pipe



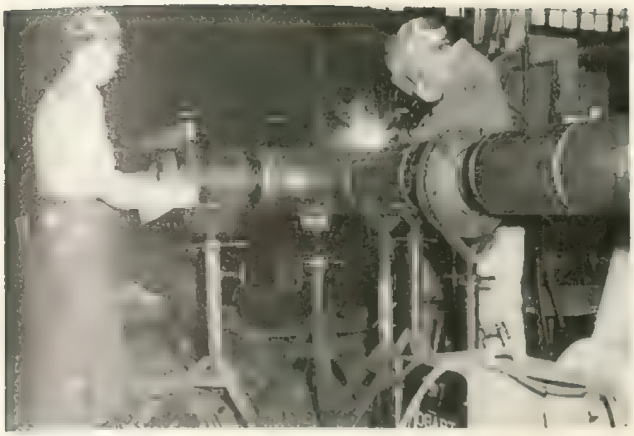
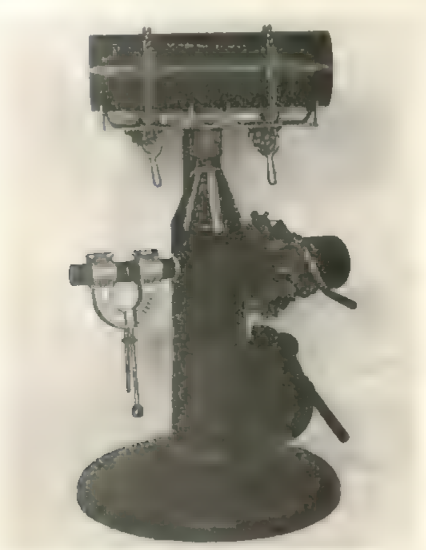


FIGURE 25-12 Shop fabrication of pipe subassembly.

FIGURE 25-13 Variety of external line-up clamps.



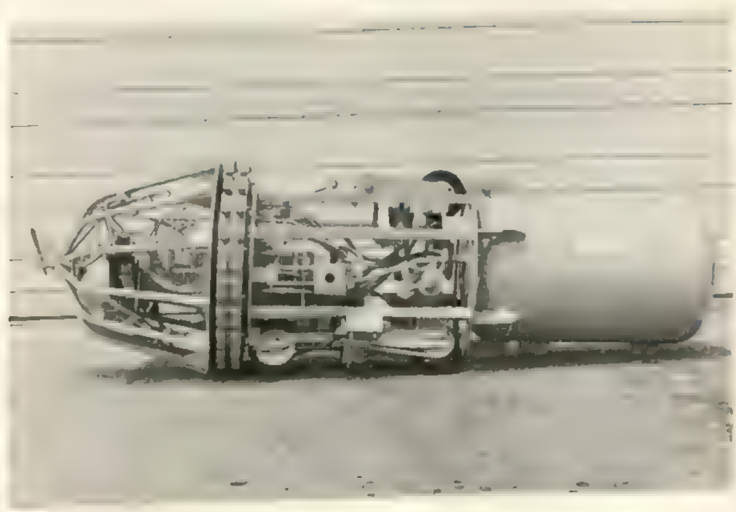
Cross-Country Pipelines

The cross-country transmission pipeline welding techniques have become extremely sophisticated. Normally, the "stove pipe" method of installing pipe is used. This means that each section or length of pipe is added on to the existing pipe installation. The crew for doing this moves along the right-of-way from the beginning to the end of the pipeline. Welding procedures and techniques vary based on the diameter of the pipe.

Special techniques were established for cross-country pipe utilizing the downhill technique and E6010-type electrodes. This technique is still used for large-diameter relatively thin wall cross-country pipeline work. More and more cross-country pipelines are being welded with semiautomatic or automatic equipment.

For the large-diameter pipe welds an internal lineup clamp is utilized (Figure 25-14). The clamp is inserted in the end of the last section of the pipeline and is operated remotely by air pressure. The air pressure clamps the internal lineup clamp to the section already welded to the pipeline and then as the new section is being placed in position, it clamps, locates, and spaces the new section. It helps round out the pipe due to the strength of the clamp. Some of these clamps include a copper backing ring. Normally, the clamps are left in the pipe joint until the first or stringer pass is made. In some cases, the second pass is also made before the clamp is released and removed from the joint. In welding large-diameter pipes there is usually one welding crew that makes the root pass and second pass, commonly known as the stringer and hot pass. They move on with the lineup clamp crew and work on the next pipe joint, and other welding crews come in to finish the weld. These crews make the so-called filler passes, which are those that fill the weld joint; the stripper passes, which are usually made in the vertical portion of the pipe joint; and the last pass, known as the

FIGURE 25-14 Pneumatic internal line-up clamps.



cap pass. The stringer crew and the other crews may represent three or four pipe welding groups that are progressing along the pipeline during its construction.

Semiautomatic welding using gas metal arc welding is also utilized for cross-country pipe welding. The welding equipment is placed on a flatbed truck or a tractor with a boom supporting the welding cables and guns over the pipe to be welded. This technique has almost doubled the production rates over manual shielded metal arc welding and has beome very popular in many parts of the world. Figure 25-15 shows the semiautomatic welding of small pipe, and Figure 25-16 shows the welding of a large-diameter cross-country pipe.

FIGURE 25-15 Welding small-diameter pipeline.

FIGURE 25-16 Welding large-diameter pipeline.

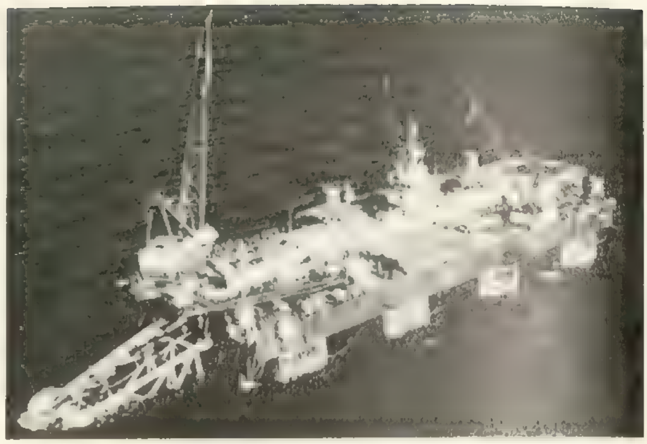


FIGURE 25-17 Air view of pipe laying barge.

Gas metal arc welding will meet the requirements of the API 1104 specification for medium and large pipe with relatively thin wall.

Pipe work very similar to the cross-country transmission pipeline welding is done on "lay-barges" (Figure 25-17). This is the welding of pipelines that will be lowered to the bottom of the ocean. Underwater pipelines bring gas and oil in from offshore wells to dry land. Manual, semiautomatic, mechanized, and automatic welding are employed by different lay-barge operations.

A high level of skill is required to make pipe welds manually or with semiautomatic equipment either uphill or downhill. Stringent qualification tests apply to pipe work. Trained and experienced welders are used for pipe welding.

Quality Assurance

The quality of butt welds in piping systems must be closely monitored. Visual inspection is always used; however, there is increasing use of ultrasonic inspection. Traditionally, x-ray inspection has been employed. The quality level, level of acceptable defects, and so on, are established by the code involved.

25-3 MANUAL AND SEMIAUTOMATIC PIPE WELDING

Neither screw-thread joints nor mechanical joints develop the full strength of pipe; hence one of the earliest applications of welding was to join pipe. The oxyacetylene welding process was used for many years to make pipe welds. Oxyacetylene welds develop the full strength of the pipe. Oxyacetylene welding is a slow welding process, so the time involved for making heavy-wall large-diameter pipe welds was excessive. However, even today the welding of 2-in. and smaller standard wall pipe is still done by the oxyacetylene welding process. It is used for radiant

FIGURE 25-18 Oxyacetylene welding of small pipe.

FIGURE 25-19 Shielded metal arc welding of heavy-wall pipe.

heating systems, cooling systems for ice rinks, and similar applications. Figure 25-18 shows the oxyacetylene welding of small-diameter pipe.

Electric arc welding has been used for pipe joining for many years. Initially, bare or lightly coated electrodes were used, and the welds produced that developed the full strength of the pipe. Recently pipelines welded with bare electrodes over 50 years ago, have been uncovered and inspection with indications that the welds were still good. The advent of the covered electrode made manual shielded metal arc welding of pipe a very popular process.

For pressure piping, primarily medium diameter, heavy wall, an uphill technique is used. This technique meets the requirements of the ASME piping codes, and literally thousands of procedures have been qualified using this technique with E6010 electrodes.

With the advent of low-alloy, high-strength steels for powerhouse construction, a new type of electrode was used. These are the low-hydrogen types with low-alloy deposited metal which will match the analysis of the pipe. This development led to welding procedures using low-alloy, low-hydrogen electrodes for powerhouse work. An illustration showing this type of application is shown in Figure 25-19.

For special applications of critical piping the root pass is made with the gas tungsten arc welding process. This is done using the open root technique or using consumable insert rings and fusing them to the root of the joint. A second pass may be made with the gas tungsten arc welding and the remaining weld deposit by shielded metal arc welding. This produces an excellent weld joint with an extremely smooth inner surface. Procedures have been developed for many different low-alloy steels, including the low-chrome–molybdenum steels.

Gas tungsten arc and shielded metal arc welding applied manually is a relatively low production welding method. When gas metal arc welding was developed, it was soon applied to pipe welding. It was used for roll welding (1G) with the hand-held gun, and for fixed position (5G) welding at construction sites. Figure 25-20 shows the use of semiautomatic gas metal arc welding in a factory installation. Both the small wire short-circuiting

FIGURE 25-20 Semiautomatic welding of power plant piping.

FIGURE 25-21 Pipe weld schedules.

Process	Joint Design (See Figure 25-10)	Method of Application	Pass	Electrode or Rod Diag. in.	Electrode or Rod Diag. mm	Amperes DC	Voltage	Shielding Details	Travel	Other Information
GTAW	A	MA	1	1/16	1.6	35–45	10–12 EN	Argon @ 12–15 ft^3/hr	Downhill	Use purge gas inside for high quality
PAW	A or D	MA	1	None	None	60–70	–EP	Argon @ 12–15 ft^3/hr	10 in./min	Plasma gas is 95% argon + 5% H_2 @ 1 ft^3/hr
GTAW	A or D	AU	1	None	None	40	10 EN	Argon @ 20 ft^3/hr	4-1/4 in./min either	1/16-in. tungsten use purge gas
OFG	B or E	MA	1 2	1/8	3.2	—	—	Product of combustion	3 in./min	Forehand—oxygen and acetylene
GTAW	E	MA	1	3/32	2.4	90–100	EN	Argon @ 15–20 ft^3/hr	Uphill	Use purge gas
			2 +	1/8	3.2	100–140	EN	Argon @ 20–25 ft^3/hr	Uphill	No purge gas
GMAW	C or E	SA	1	0.035	0.8	150–170	22 EP	CO_2 @ 12–15 ft^3/hr	Downhill	Travel 11 in./min
			2 +	0.035	0.8	120–130	20 EP	CO_2 @ 12–15 ft^3/hr	Up or down	Travel 4 in./min
SMAW	C	MA	1	1/8	3.2	90–100	EP	Coating	Uphill	E6010
			2 +	1/8	3.2	110–140	EP	Coating	Uphill	E6010
SMAW	E	MA	1	1/8	3.2	80–120	EP	Coating	Downhill	E6010
			2 +	1/8	3.2	150–200	EP	Coating	Downhill	E6010
GTAW	E or F	MA	1 + 2	3/32	2.4	90–100	EN	Argon @ 15–20 ft^3/hr	Uphill	Alt. use insert
SMAW			3 +	5/32	4.0	120–200	20– EP	Coating	Uphill	Low hydrogen
SMAW	C	MA	1	5/32	4.0	140–160	24–26 EP	Coating	Downhill	E6010 or E7016
			2 +	3/16	4.8	160–190	24–28 EP	Coating	Downhill	E6010 or E7016
GMAW	C or E	SA	1 +	0.035	0.8	180–200	21-23 EP	CO_2 @ 20–30 ft^3/hr	Downhill	Less passes for downhill
			1 +	0.035	0.8	120–150	19–20 EP	CO_2 @ 20–30 ft^3/hr	Uphill	
FCAW	C or E	SA	1	0.045	0.9	135–145	20–21 EP	CO_2 @ 20–30 ft^3/hr	Uphill	Use purge for high quality
			2 +	3/32	2.4	325–350	25–28 EP	CO_2 @ 25–30 ft^3/hr	Uphill	
SMAW	E or F	MA	1	1/8	3.2	90–100	EP	Coating	Uphill	EXX10 electrode
			2 +	5/32	4.0	120–140	EP	Coating	Uphill	Low-hydrogen elec.
SAW	E or F	AU	1	5/32	4.0	375–425	23–25 EP	Sub arc flux	20 in./min	Backup ring rqd.
			2 +	5/32	4.0	480–505	26–27 EP	Sub arc flux	26 in./min	Flat-roll
GMAW	C,E,F	SA or AU	1	0.035	0.8	150–170	20–22 EP	CO_2 @ 20–35 ft^3/hr	12 in./min	Flat-roll
SAW		AU	2 +	5/32	4.0	480–505	26–27 EP	Sub arc flux	26 in./min	Double ending
GMAW	C,E,F	SA or AU	1	0.035	0.8	150–170	20–22 EP	CO_2 @ 20–35 ft^3/hr	12 in./min	Flat-roll
FCAW		AU	2 +	3/32	2.4	350–400	25–28 EP	CO_2 @ 30–35 ft^3/hr	10 in./min	Double ending
FCAW	C or E	SA	1	0.045	0.9	135–145	20–21 EP	CO_2 @ 20–30 ft^3/hr	Uphill	Use purge for high quality
			2 +	3/32	2.4	325–350	25–28 EP	CO_2 @ 25–30 ft^3/hr	Uphill	
GTAW	C or E	MA	1 + 2	3/32	2.4	90–100	EN	Argon @ 15–20 ft^3/hr	Uphill	Alt. use insert
FCAW		SA	3 +	3/32	2.4	325–350	25–28 EP	CO_2 @ 25–30 ft^3/hr	Uphill	
GTAW	C or E	MA	1 + 2	3/32	2.4	90–100	EN	Argon @ 15–20 ft^3/hr	Uphill	Alt. use insert
GMAW		SA	3 +	0.035	0.8	120–150	19–20 EP	CO_2 @ 20–30 ft^3/hr	Either	

technique and the spray technique are employed. Electrode wire compositions were developed to match the composition of various base metals. Flux-cored electrode wires were also formulated to match the composition requirements for pressure piping.

The work just described is governed by codes and specifications. A summary of pipe welding schedules is given in Figure 25-21. Assistance in developing pipe welding procedures is provided by the welding society in the form of recommended practices. A listing of these is given in Figure 25-22. These are available from AWS, Miami, Florida.

D10.4	Austenitic chromium–nickel, stainless steel piping and tubing
D10.6	Gas tungsten arc welding of titanium piping and tubing
D10.7	Gas shielded arc welding of aluminum and aluminum alloy pipe
D10.8	Chromium–molybdenum steel piping and tubing
D10.10	Local heat treatment of welds in piping and tubing
D10.11	Root pass welding and gas purging
D10.12	Welding plain carbon steel pipe

FIGURE 25-22 AWS recommended practices for pipe welding.

25-4 MECHANIZED PIPE AND TUBE WELDING

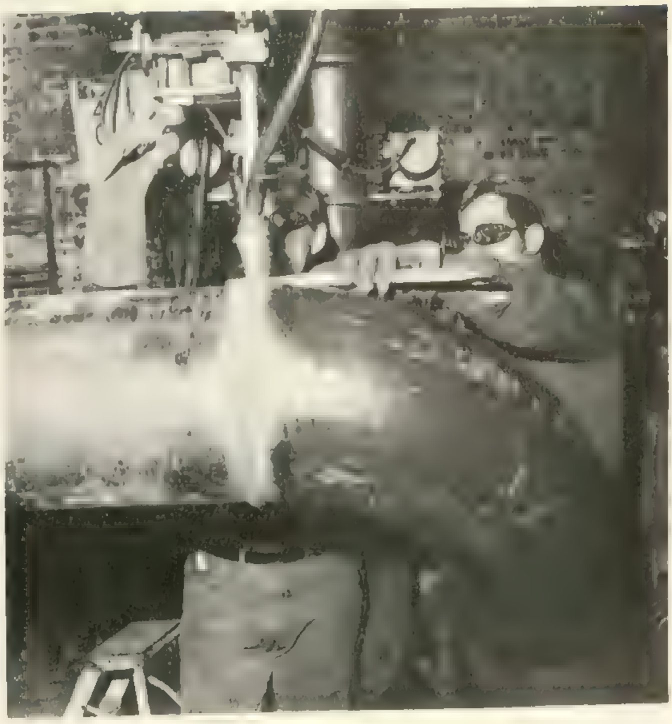
Mechanized welding systems are available for welding pipe and tubing. Two basic types of procedures are used for different applications. One is "roll welding" pipe in the flat or downhand position, the 1G position, when the joint is rotated under the welding head. The second, known as "orbital welding," is used when the pipe is in the fixed position, with the axis of the pipe horizontal or vertical, and the machine rotates about the pipe to make the weld. A further subdivision is for thin- or heavy-wall pipe, or for small- or large-diameter pipe or tubing. A further subdivision relates to the weld process. Submerged arc welding is used for roll welding only; other processes, such as gas metal arc, flux-cored arc, and gas tungsten arc, are used for making pipe welds in any position.

Roll welding, that is, rotating the pipe under the welding head, was the first application of machine or automatic welding. In the field this is known as "double jointing" (Figure 25-23). This means the welding together of two sections of straight pipe normally done for cross-country pipelines. Double jointing is done at the pipe storage yard using standard lengths of pipe which are welded and then transported to the construction site. Roll welding is more productive than orbit welding and reduces the total number of welding hours to construct a pipeline.

FIGURE 25-23 Double joining pipe by roll welding.

Submerged arc welding has historically been used for roll welding. An internal line-up clamp, usually containing a backup bar, is used. Roll welding is also done in the fabricating shop on subassemblies. Normally straight pipe sections are joined to ells, flanges, and so on. (Figure 25-24). This provides higher efficiency since welds can be made more rapidly in the flat or roll position than in the fixed position. In some cases, the first or root pass, and even a second pass, is made by gas metal arc welding, shielded metal arc welding, or gas tungsten

FIGURE 25-24 Roll welding in pipe fabrication shop.



arc welding. Flux-cored arc welding or gas metal arc welding can be used for subsequent passes, as well as submerged arc welding.

The plasma arc process using the keyhole mode is also used for roll welding. This requires complex controls since there are a large number of variables involved and the closing of the keyhole requires simultaneous coordinated change in parameters. This is used on medium-wall alloy and stainless steel pipe.

Orbital welding of thin-wall tubing and standard wall pipe is being done with the gas tungsten arc welding process. Mechanized orbital tube and pipe welding systems are used (Figure 25-25). They are available as complete systems consisting of the power source, programmer, welding head, and so on (Figure 25-26). Remote control pendants or controls on the head allow operation at the point of welding. This equipment can weld tubes with an outside diameter from ¼ in. (6.35 mm) to over 8 in. (200 mm), with wall thicknesses from 0.015 in. (0.35 mm) up to ½ in. (6.35 mm). Exact capabilities depend on the welding head design as well as the joint design and pipe material. The head shown in Figure 25-27 is designed with a minimum radial clearance of 1¹³⁄₁₆ in. (46 mm), so that it can be used to weld pipe in clusters. These mechanized orbital heads for pipe and tubing are compact and rugged and clamp on the pipe or tube. A family of heads is required to weld the smallest to the larger tubes. The welding torch rotates around the pipe and carries the tungsten electrode. In some designs, slip rings are used to avoid rotating or twisting cables and hose. These heads will rotate the torch around the pipe continuously. Other heads, which do not include slip rings, allow the cable and hose to wrap around the pipe. Three revolutions are usually the maximum used. A clam-shell head design (Figure 25-28) is used for smaller tubes.

The three joint types commonly used are shown in Figure 25-29. This includes the square groove joint, socket joint, and U-groove joint. The square groove joint is used for thin-wall tubing and only a single pass is used. Socket joints provide easy fitup and the weld is a fillet. Groove joints, U and V, are used for thicker-wall tubing where full-penetration welds are required. Multiple passes with filler metal are used for groove joints.

Specialized programmers having upslope and

FIGURE 25-25 Orbital head welding tubing.

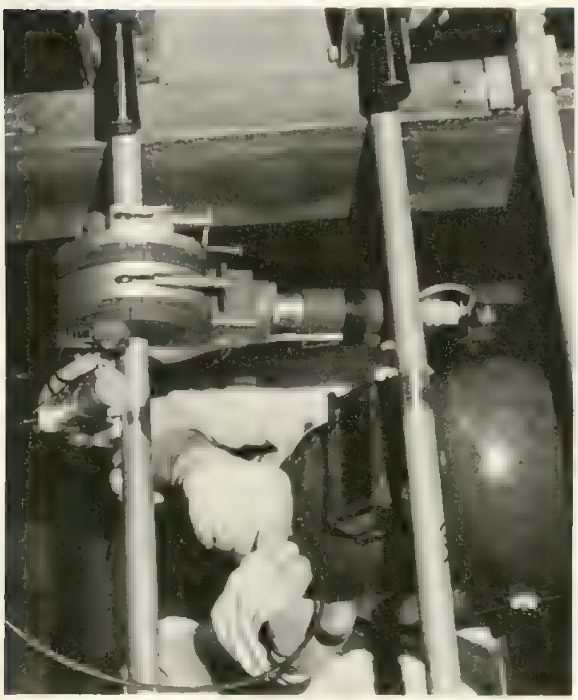


FIGURE 25-26 Complete system for welding small-diameter tubing.

FIGURE 25-27 Tube-to-tube orbital head for GTAW.

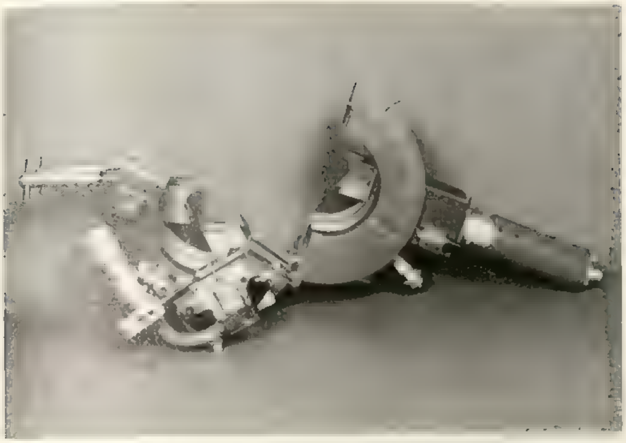
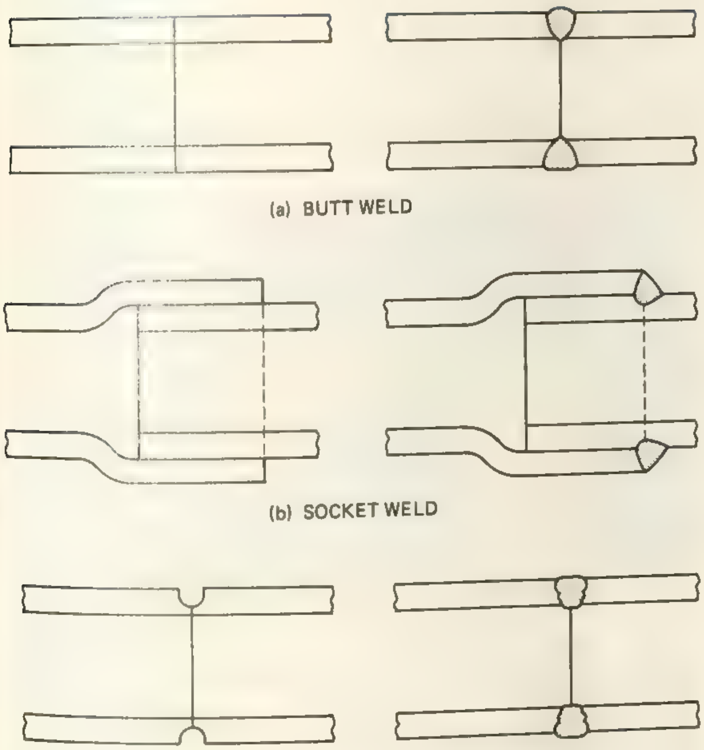


FIGURE 25-28

FIGURE 25-29



downslope of welding current plus control of rotation, preflow and postflow of gas, and high frequency for arc initiation are all included. Pulsing is normally used for most mechanized welding procedures.

For larger-diameter pipe with thicker wall, a different type of gas tungsten welding head is used. A head of this type rotates around the pipe but is held to the pipe by means of a split-ring or chain-drive assembly (Figure 25-30). Some units have a low profile and can weld pipe with minimum clearance. This machine includes a wire

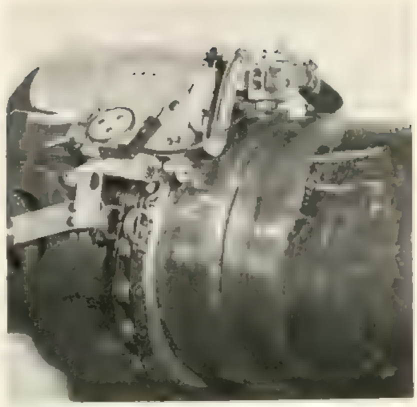


FIGURE 25-30 Mechanized pipe welding head for heavy-wall pipe.

feeder and various collets to weld different sizes of pipe. It can also be used for welding pipe when it is in the vertical position (Figure 25-31). Groove joints are normally employed.

Similar machines have been developed that utilize a combination of welding processes. The first pass will use gas tungsten arc, and subsequent passes may use the gas metal arc. Torches are changed for making the total weld. This equipment is becoming increasingly popular for welding pressure piping. Complex controllers and two power sources or combination power sources with CC and CV characteristics are required.

Mechanized welding machines for welding large-diameter pipe, primarily cross-country pipelines, use the gas metal arc welding process. These are large machines that fit around the circumference of the pipe and will make gas metal arc welds in the field, on lay-barges, or in the shop. Different types are available that utilize dif-

FIGURE 25-31 Mechanized pipe welding with pipe vertical.

ferent weld joint details. In some cases, welds are made on the inside diameter of the pipe as well as the outside diameter. The inside welding head is combined with a line-up clamp and is made prior to the outside weld. Equipment of this type is shown in Figure 25-32.

Mechanized pipe welding systems will continue to advance and in some cases become automatic or automated.

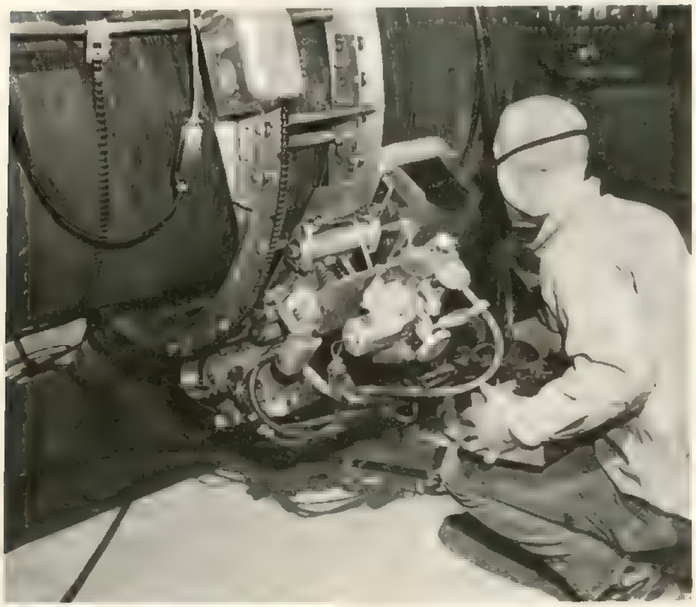


FIGURE 25-32 GMAW welding machine for large pipe.

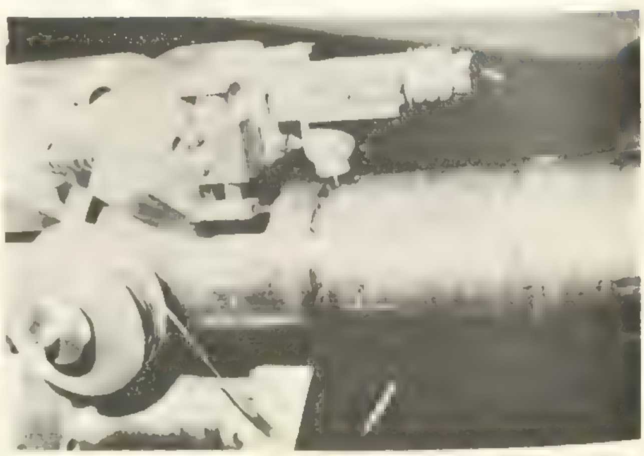
25-5 AUTOMATED PIPE WELDING

Further efforts to reduce the cost of pipe welding have resulted in a fully automated pipe welding system that is computer driven. Figure 25-33 shows the automated pipe welding system for making all-position gas tungsten arc welds on small-diameter pipe. The cabinet on the left includes the microprocessor controller, computer keyboard and display screen, and a 150-A inverter power source. This equipment includes a remote teaching pendant, shown with the automatic head in Figure 25-34. The welding head on the pipe is shown in Figure 25-35. This head weighs approximately 25 lb and will weld pipe sizes from 1¾ to 2½ in. nominal with a standard wall to the heaviest pipe wall available. This head was designed for minimum radial clearance between adjacent pipes, so that welds can be made when the pipe is separated by only 2½ in. The head hinges in the middle in a clamshell fashion. Slip rings are used to transmit welding current, control signals, and shielding gas so that cables and hose do not wrap around the pipe during operation. Functional motors for torch rotation, oscillation, tungsten-to-work distance, and cold wire feeder are all built into the housing of the head.

FIGURE 25-33 Automated pipe welding system

FIGURE 25-34 Automated head and remote pendant.

FIGURE 25-35 Pipe head on pipe.



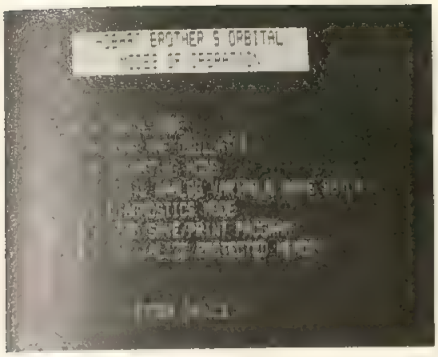


FIGURE 25-36 Program menu.

The heart of this automated welding system is the microprocessor controller. The input to the controller is by means of the keyboard and the readout on the monitor screen. The microprocessor controls all functions; however, the arc length control may be a subroutine using a separate system. The key to operation is the software program, which is extremely complex but is user friendly. The initial readout observed by the operator is the mode of operation and menu (Figure 25-36). The operator selects the teach mode, which is the next display. Specific instructions for orbital welding is given in the next display. The operator will then key in the welding parameters as requested and they will appear on the next display, which is the operating mode. This input provides welding parameters for making the weld utilizing a specific procedure based on pipe size, wall thickness, joint details, pipe analysis, and so on. This procedure can be modified and the procedure can be recorded by means of a hard-copy printout at any step. Welding operators learn to program this equipment in a short time, based on their experience.

In operation, the head is normally clamped on the pipe and lined up with the joint. The root pass does not require oscillation; however, subsequent passes may utilize oscillation as required. Oscillation is programmed with the exact dimensions, which change for each layer. Dwell time is programmed for each end of the stroke, and for each layer, the speed of oscillation is also programmed and welding current pulsing is synchronized with oscillation. When the second pass is completed, the programmer automatically changes to the third pass without stopping the weld. Welding parameters can be changed each 10° around the pipe. The welding is uninterrupted from root to cap pass and provides 100% arc time. When the final pass is completed, the controller turns off the machine.

Welds produced by this automated system meet the requirements of the most stringent codes. Radiographs of welds produced are water clear.

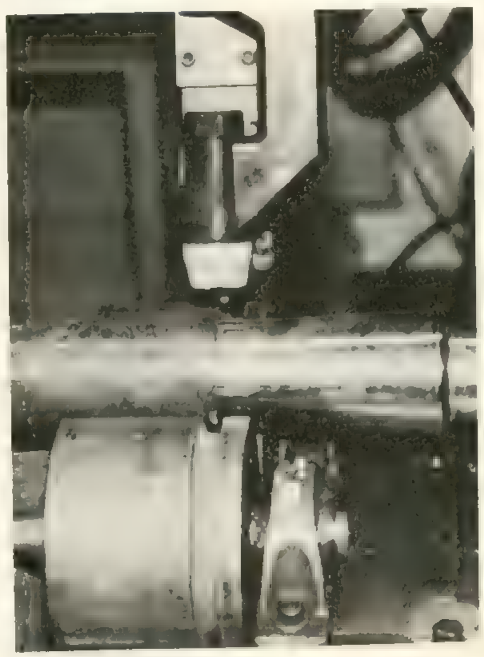
The teach pendant shown earlier is used to input information to the microprocessor to establish the total welding procedure. Arc sensing is used to control oscillation. This allows the head to mechanically oscillate during setup to determine the centerline of the weld joint prior to striking an arc. The arc will sense the joint at each end of the oscillation stroke. The controller will reverse the stroke and keep the weld head centered on the joint. This can be modified for a split weave technique and can be different for each layer.

Practical application in a fabrication shop utilizes two heads with one controller and power source panel. While one head is making welds, the other head is being attached and aligned to another joint. When the first joint is completed, the controller switches to the second head and makes the weld. Meanwhile the first head is removed from the completed pipe joint and attached to a new joint ready to be welded.

This machine can be utilized for remote welding in dangerous or radioactive atmospheres.

Automated welding has been applied to the plasma arc welding, keyhole mode process for roll welding. In this case the torch is stationary, but adjustable, while the pipe joint rotates under the arc. The welding head has automatic *X*, *Y*, and *Z* adjustments. The angle of the torch is preset. The microprocessor initiates the plasma arc and all other functions, including torch adjustment, pipe rotation, and gas coverage. Welding parameters are programmed to initiate the keyhole and to provide filler metal. This equipment is designed for high-alloy steel piping and is normally used with single-pass operation. Upon completion of the weld, the computer programs the closing of the keyhole, which involves simultaneous changing of four variables. This equipment is shown in Figure 25-37.

FIGURE 25-37 Roll pipe welding equipment: plasma.



25-6 TUBE TO SHEET WELDING

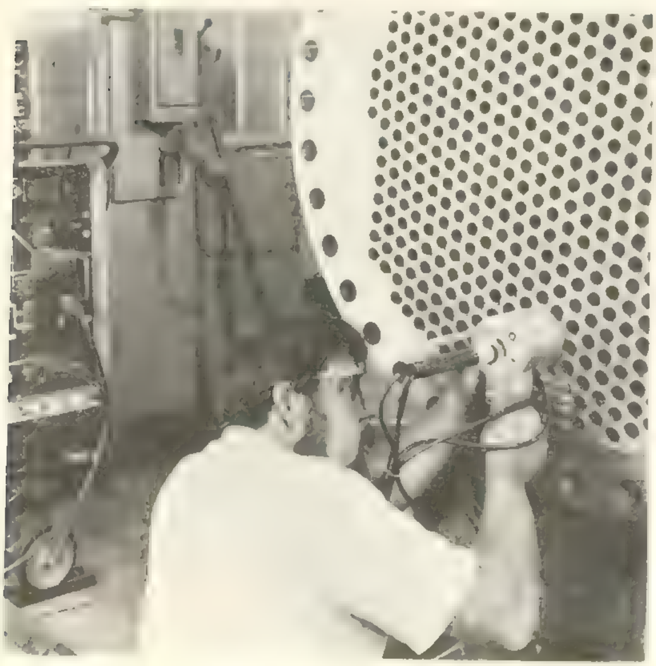
Mechanized equipment is widely used for welding tubes to tube sheets or heads. This equipment is used primarily by the heat-exchanger industry. A heat exchanger consists of many tubes between two headers, where the tubes must be attached to the headers with perfect, leakproof connections. Each heat exchanger may have hundreds of tube-to-header joints. Previously, these were mechanically connected or manually welded with gas tungsten arc welding, which was a tedious boring job. The transition from manual to machine welding has improved quality and reduced the cost per weld.[5]

Complete welding systems are available, including the mechanized orbital welding head, the welding power source, and the programmer, which completely mechanize the welding operation.

The welding head is a compact lightweight device that rotates the gas tungsten arc welding torch around the periphery of the tube to sheet joint. The head includes a mandrel which fits inside the tube to be welded and locates the torch. The head will rotate the torch 360° plus overlap in each direction. Slip rings are incorporated so that the hose and cables do not twist. Figure 25-38 shows this equipment in use welding a small heat exchanger. This photograph shows the tube sheet in the vertical position; however, the equipment can be used if the tube sheet is horizontal and the weld is flat or even if the weld is overhead.

Heads of this type can weld tubes with outside diameter from ⅝ in. (16 mm) to 6 in. (150 mm) with a tube wall thickness of 0.015 in. (0.4 mm) and larger.

FIGURE 25-38 Tube-to-sheet mechanized welding machine.



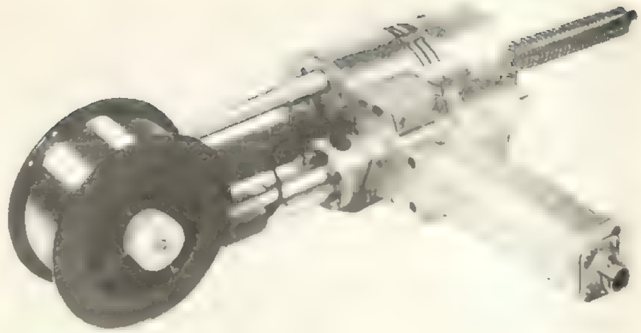


FIGURE 25-39 Tube-to-tube sheet welding head.

A close-up of the welding head is shown in Figure 25-39. The head includes the GTAW torch, rotation motor and filler wire, and drive motor. The tungsten electrode is the 2% thoriated type (AWS Spec. EWTh2) and $\frac{3}{32}$ in. diameter is normally used. Filler metal can be added for certain types of welds. When filler metal is added, the arc length should be slightly greater than the electrode diameter. When filler metal is not added, the arc length is slightly less than the electrode diameter.

The tungsten electrode position is adjustable and critical for tube-to-header welds. Figure 25-40 shows the electrode position for the most common joint designs.

The programmer is the same as used with mechanized tube-to-tube welding heads. It starts the gas preflow, torch rotation, high frequency, and welding current, which normally changes during the weld cycle. Pulsing is normally used for making tube-to-tube sheet welds. The controller has various delays and ends with postflow of shielding gas, required to produce high-quality welds. The equipment may also include a weld control pendant, which is used when remote welding is required.

The joint detail used for this type of welding is shown in Figure 25-41. The three most common joint designs are the extended tube, flush tube, and recessed tube. There are variations of each design. Some applications require only a seal bead between the tube and the tube sheet. Filler metal is normally added for the extended tube or the recessed tube joint design. Nuclear specifications require that the weld metal thickness be equal to the thickness of the tube, which dictates the J-groove joint design. The fillet weld design normally will not produce the desired cross section dimension since the fillet weld throat dimension is less than the thickness of the tube. The design selected must have sufficient filler metal so that the weld is stronger through its shortest dimension than the thickness of the wall of the tube. Joint design is based on the specifications involved. The welding procedure shown is with the tube sheet vertical. With the tube sheet flat, higher currents can be used. Any metal welded by the gas tungsten arc process can be welded with mechanized GTAW tube-to-tube sheet welding heads.

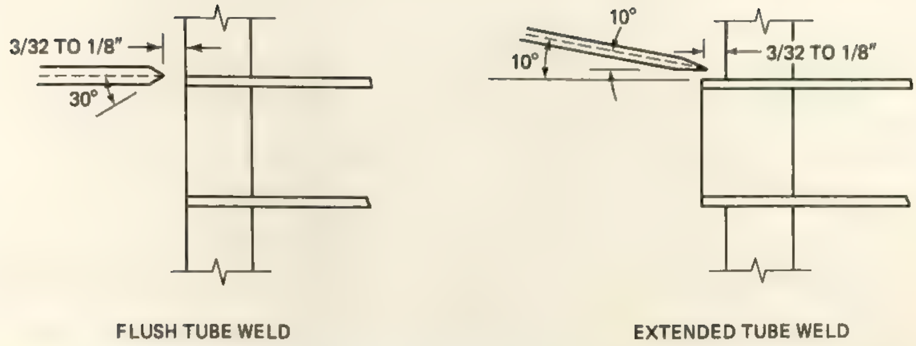
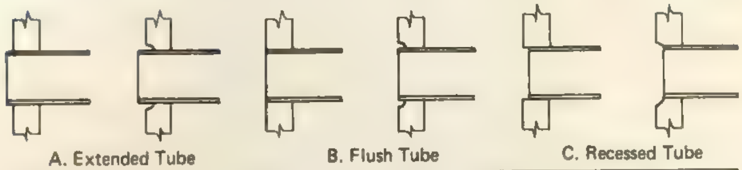


FIGURE 25-40 **Tungsten electrode position for welds.**

FIGURE 25-41 **Tube-to-tube sheet welding schedule.**



Tube O.D. in.	Tube O.D. mm	Wall Thickness in.	Wall Thickness mm	Joint Type	Weld Current (Amperes)	Filler Rod Type	Weld Time (sec)
Stainless steel tube-to-stainless steel tube sheet							
0.75	19.1	0.062	1.6	A	140	E304	18
0.75	19.1	0.080	2.0	A	130	None	18
0.75	19.1	0.090	2.3	A	140	E304	31
Mild steel to mild steel							
0.75	19.1	0.062	1.6	B	140	E705-3	28
1.00	25	0.125	3.2	B	140	E705-3	184
1.00	25*	0.125	3.2	C	180	E705-3	49
2.50	62	0.187	4.7	B	175	E705-3	245
Stainless steel to mild steel							
0.62	15.7	0.062	1.6	A	120	E309	14
1.00	25	0.083	2.1	A	155	E309	40
CuNi-CuNi							
0.75	19.1	0.062	1.6	A	160	ERCuNi	28
CuNi–mild steel							
0.75	19.1	0.062	1.6	A	160	ERNiCrFe-6	28
Cu–mild steel							
0.62	15.7	0.025	0.6	A	140	ERCuSi-A	16

*2 passes

QUESTIONS

25-1. What are the seven different classifications of pipe and tubing?

25-2. What schedule number pertains to standard wall pipe?

25-3. Briefly describe a continuous pipe mill.

25-4. What arc welding process is used to make spiral joint pipe?

25-5. What percentage of steel produced is made into tubular products?

25-6. What code applies to most high-pressure pipe welding? Cross-country pipe?

25-7. Can more than one welding process be used to make a pipe weld? Explain.

25-8. Why are different pipe weld joint designs used? Where is each used?

25-9. Explain the difference between internal and external line-up clamps. What determines the type to be used?

25-10. Explain the difference between uphill and downhill pipe welding.

25-11. What type of covered electrode is widely used on cross-country pipe welding?

25-12. What is stove pipe welding?

25-13. What is double jointing?

25-14. What is the difference between roll welding and fixed-position welding?

25-15. Can submerged arc welding be used for fixed-position welding? For roll welding?

25-16. Are low-hydrogen welding electrodes used for pressure piping?

25-17. What is the advantage of consumable inserts for pipe welding?

25-18. Can gas metal arc welding be used on pipelines?

25-19. What is the advantage of mechanized orbital welding of tubes?

25-20. What are the three joint types for tube-to-tube sheet welds?

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26

Special Applications of Welding

26-1 ARC SPOT WELDING

An arc spot weld is a spot weld made by an arc welding process. A spot weld "is a weld made between or upon overlapping members in which coalescence may start and occur on the faying surfaces or may proceed from the outer surface of one member." The weld is approximately circular. Figure 26-1 shows the different spot welds. An arc spot weld differs from the resistance spot weld since in resistance welding coalescence is located at the faying surfaces of the parts being joined.[1] The arc spot weld does not require a hole in either member. Therefore, it differs from the plug weld, which requires a hole to be prepared for the weld.

Arc spot welding is performed by melting through one of the members, usually the top member. The thickness of this member is the limiting factor. This limiting factor also depends on the welding process used.

The gas tungsten arc and the gas metal arc welding process are most commonly employed for making arc spot welds. Flux-cored arc welding, and shielded metal arc welding using covered electrodes can be used.

The principal operation of arc spot welding is to strike and hold an arc without travel at a point where the two parts are held tightly together. The heat of the arc melts the surface of the top member and the depth

OUTLINE

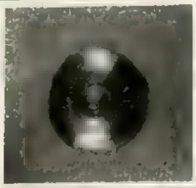
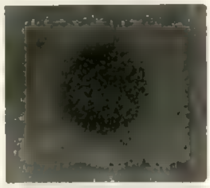
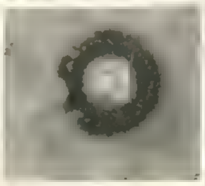
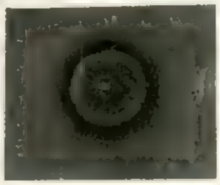
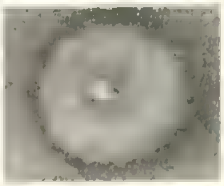
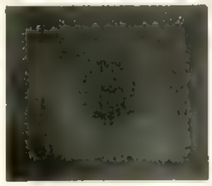
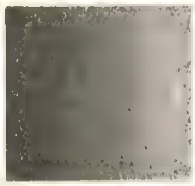
Material	Mild Steel	Mild Steel	Mild Steel	Stainless	Aluminum
Thickness	20 ga (0.0359 in.)	11 ga (0.1196 in.)	3/16 in.	22 ga (0.0299 in.)	11 ga (0.0907 in.)
Process	GMAW (CO_2)	GMAW (CO_2)	FCAW (CO_2)	GTAW (Argon)	GMAW (Argon)
Electrode size	0.035 in.-.9 mm	1/16 in.-1.6 mm	7/64 in.-2.8 mm	---	3/64 in.-1.2 mm
Electrode type	E70S-3	E70S-3	E70T-1	---	5356
Top side					
Bottom side					
Cross section					

FIGURE 26-1 Spot welds: top, bottom, and cross section.

of the melting is dependent on the welding process, the electrode size and type, the welding current and the time, and, in the case of gas metal arc welding, the type of shielding gas employed. Timing is usually done automatically by means of a timer. With the exception of the timer and special electrode holders or guns, the process utilizes the same equipment that is normally used for that process.

Arc spot welding is an extremely adaptable process that offers many metal joining advantages. One advantage is that it can be used without exercising manipulative skills. Thus, the training required to make arc spot welds is minor. In addition, the welder making arc spot welds does not have to use a welding helmet since the arc is contained within a gun or gun nozzle. Arc spot welding is an extremely fast process, can be used for a variety of joining requirements, and can be fully automated.

The arc spot welds can be made in the flat position and in the horizontal position, but it is almost impossible to make arc spot welds in the overhead position. The reason for this is that the sheet or member closest to the welding gun must melt completely through and this can result in a fairly large mass of molten metal which tends to fall away from the weld in the overhead position.

The metals normally welded with arc spot welding are the mild, low-alloy and stainless steels. However, with special precautions other metals can be welded. Aluminum can be arc spot welded if a clean interface between the parts to be joined is maintained.

Thickness range of metals that can be welded by the different arc processes is shown in the schedules for GTAW and GMAW welding. This information involves the thickness of the top of the member which must be melted through. The thickness of the other member is not important. Lap joints are the most common types of joints used for arc spot welding; however, tee joints can also be made.

Gas Tungsten Arc Spot Welding

Arc spot welding with the gas tungsten arc process is an extremely efficient and simple way to make weld joints. The process is limited to a maximum thickness of 1/16 in. (1.6 mm) of the top sheet or the sheet closest to the arc. Gas tungsten arc welding can be used for mild steels, low-alloy steels, stainless steels, and aluminum alloys.

A special welding gun or torch, designed for arc spot welding must be used. The nozzle of the gun is used to apply pressure to hold the parts being welded in close contact. A gun for gas tungsten arc spot welding is shown in Figure 26-2. The gun nozzle is made of copper or stainless steel and is normally water cooled since the arc is

FIGURE 26-2 Making a GTAW spot weld.

contained entirely within the nozzle. The nozzle design controls the critical distance between the tungsten electrode and the surface of the work; it should have ports for the shielding gas to escape. The inside diameter should be related to the size of the tungsten electrode being used. The 0.500-in. (12-mm) inside diameter is most common. The nozzles can also be designed to help locate the arc spot weld, especially with respect to corners or edges of the top sheet. Arc spot welding equipment can be used to make tack welds at inside or outside corner joints, etc. The gas tungsten arc spot gun includes a trigger switch which will actuate the arc spot operation.

A timer or controller is required. Some gas tungsten arc power sources include timers, which are preferred. However, if these are not included, a separate timer can be used provided that the power source includes a contactor. The timer should have the capability of being adjusted from 0.5 second up to 5 seconds.

The tungsten electrode type would be the same as would be normally selected for the material to be welded. The ⅛-in. (3.2-mm) electrode diameter is recommended for all work. The point of the tungsten should be the standard ground point but then squared off or blunted on the very end. This tends to improve the depth of penetration obtained. An arc length of $\frac{1}{16}$ in. (1.6 mm) is recommended. If the arc length is too short the weld area or spot weld size will be small. As the arc length increases the size of this arc spot weld will be larger. If the arc length is too long, an unstable arc will result and there will be a lack of uniformity between the different arc spot welds.

The normal sequence of events is: The nozzle of the torch or gun is placed on the joint and sufficient pressure is applied to bring the parts in intimate contact. The trigger on the gun is depressed, which starts the welding cycle. Gas flow is initiated to purge the system and the area within the gun nozzle. If water cooling is employed the cooling water will also start to flow. The arc will be initiated by the high-frequency discharge supplied by the power source. The arc will continue for the period of time established and will be extinguished as the contactor opens. The shielding gas will continue to flow for a predetermined postflow time. This completes the normal cycle.

Normally, the thinnest metals joined are 24 gauge, which is 0.022 in. (0.56 mm). If both top and bottom sheets are of the same thickness, it is best to utilize a copper backup to prevent the weld from falling through the joint and having a depression on the top and excessive penetration on the bottom. A schedule for gas tungsten arc welding is shown in Figure 26-3. It is best to use high current and short time cycle rather than lower currents with longer time period. The amount of current increases the size of the nuggets and the thickness of the materials that can be welded. Nugget diameter and strength is also influenced by the welding current. The time factor tends to increase penetration but to a much lesser degree than the current. If too much current is used, it can cause splashing. This flowing away of the molten metal from the top member may contaminate the tungsten and will result in an unsatisfactory weld. If the current is too low, the nuggets may not penetrate completely through the top sheet to the bottom sheet.

The shielding gas will be either argon or helium with a flow rate of from 6 to 10 ft^3/hr (2.5 to 4.5 liters/min). Helium will provide a smaller weld nugget with a greater depth of penetration. Argon produces a larger weld nugget with penetration not quite so deep.

Direct current should be used for all materials, except aluminum, with the electrode negative (straight polarity). Alternating current with continous high frequency should be employed on aluminum. If aluminum is well cleaned, the electrode negative (straight polarity) can be used. Parts to be welded should be clean of oil, dirt, grease, scale, and so on. This is especially true at the interface and absolutely necessary when welding aluminum. The weld diameter is the basis for the shear strength of arc spot welds. The shear strength will be similar to resistance spot welds made in the same material.

Gas tungsten arc spot welding is widely used in the manufacture of automotive parts, parts for appliances, precision metal parts, and parts for electronic components. It is normally applied as a semiautomatic process; however, it can be mechanized or automated and used for high-volume production work.

Gas Metal and Flux-Cored Arc Spot Welding

The gas metal arc and the flux-cored arc welding processes can both be used for making arc spot welds. The equipment used for the two processes is identical. The difference is in the type of electrode wire employed.

Material Type	Metal Thickness (top sheet) Gage	in.	mm	Welding Conditions Amperes DCEP + HF	AC-HF	Arc Spot Time Seconds	Shielding Gas Argon CFH	L/M
Stainless Steel	24	0.025	0.64	125	175	1.0	10	4.5
	24	0.025	0.64	110	175	1.25	10	4.5
	24	0.025	0.64	100	150	1.5	10	4.5
	22	0.031	0.79	125	175	1.5	10	4.5
	22	0.031	0.79	100	175	1.75	10	4.5
	18	0.050	1.27	140	200	1.5	12	5.6
	18	0.050	1.27	110	150	2.5	12	5.6
	16	0.062	1.57	170	250	3.0	12	5.6
	16	0.062	1.57	140	—	3.25	12	5.6
	16	0.062	1.57	115	—	5.25	12	5.6
		0.064	1.62	160	250	2.25	12	5.6
Mild Steel	22	0.031	0.79	170	250	1.5	8	3.6
	22	0.031	0.79	140	200	2.0	8	3.6
	22	0.031	0.79	120	175	2.25	8	3.6
	18	0.050	1.27	170	250	1.75	10	4.5
	18	0.050	1.27	140	200	2.0	10	4.5
	18	0.050	1.27	135	200	2.5	10	4.5
	16	0.062	1.57	170	250	3.0	12	5.6
	16	0.062	1.57	155	225	3.5	12	5.6
Aluminum		0.022	0.56	—	170	1.1	8	3.6
		0.032	0.81	—	200	1.5	8	3.6
		0.048	1.21	—	220	1.7	8	3.6
		0.064	1.63	—	250	2.2	8	3.6

Note: 1. The electrode is 2% thoriated tungsten, except for aluminum pure tungsten electrodes are used, 1/8 in. diameter.
2. High-frequency is used to start the arc when using direct current and alternating current.
3. Arc length electrode to work 1/16.

FIGURE 26-3 Schedule of arc spot welds using GTAW.

The arc welding equipment used for normal semiautomatic welding can be used for gas metal and flux-cored arc spot welding by the addition of a timer and a special torch or gun nozzle. Time range for the timer should be the same as used for gas tungsten arc spot welding. The nozzle or torch should be sufficiently strong so that it can transmit the force to hold the parts to be welded together in intimate contact.

The sequence of events to produce an arc spot weld are almost the same as used for gas tungsten arc welding. The only difference is that when the arc starts the wire feeder will feed electrode wire into the arc.

The gas metal and flux-cored arc processes can weld through greater thicknesses of metal than gas tungsten arc spot welding. With proper conditions, welds can be routinely made through the top plate of ¼ in. (6.4 mm) thickness. At the other end of the scale, welds can be made in 24-gauge material 0.022 in. (0.56 mm) thick. Welding is done primarily on the mild steels and low-alloy steels. Figure 26-4 shows an arc spot weld being made.

The shielding gas normally used for gas metal arc spot welding is CO_2. Carbon dioxide is selected since it has the highest penetrating qualities of any of the

FIGURE 26-4 Making a GMAW or FCAW [illegible] weld.

shielding gases. If high penetration is not required, the 75% argon–25% CO_2 mixture can be used.

The size and type of electrode wire have a large effect on the depth of penetration and on the diameter of the weld nugget at the interface. Normally, for maximum strength of the arc spot weld it is desirable to have a large nugget at the interface. The composition of the electrode wire should be of a deoxidized type; normally, the E70S1 electrode wire is used with solid wires or the E70T1 electrode wire is used for the flux-cored arc welding process.

The weld schedule for making GMAW and FCAW arc spot welds is shown in Figure 26-5. The electrode wire changes from a small diameter of 0.030-in. (0.8-mm) solid wire up through 1/16-in. (1.6-mm) solid wire and to 3/32-in. (2.4-mm) diameter flux-cored wire to accommodate all the weld thicknesses shown. The larger-diameter wires provide higher strength per arc spot weld, since they produce larger nuggets at the interface.

When welding thinner materials, a backup bar should be used behind the second sheet. It is also possible to make arc spot welds through more than two sheets, provided that the combined thickness of the top two sheets is within the range of the welding schedule. Intimate contact is required. The same equipment with timers can be used for tack welds and for plug welds when the top sheet is too thick.

The advantages of arc spot welds over resistance spot welds are as follows:

1. Access is required only to the top or front side of the joint.
2. The amount of pressure is not excessive, assuming that the parts are fitted properly.
3. Operator skill is minimum and a welder's helmet is not required.
4. The consistency and reproducibility of arc spot welds are excellent.
5. The amount of weld spatter, smoke, and flash is minimum and metal finishing can be eliminated for many products.
6. Distortion is minimum.
7. Close cost control is obtained using arc spot welding.
8. It is readily adaptable to designs originally used for bolting or riveting.

Arc spot welding is being used in automobile body

FIGURE 26-5 Schedule of arc spot welds using FCAW or GMAW.

Gage	Material Thickness in.	mm	Electrode Wire Dia. in.	mm	Electrode Type	Current DC Amperes	Arc Voltage EP Volts	Arc Spot Time Seconds	Wire Consumed Per Spot in.	mm	Typical Shear Strength Per Spot lbs	kg
24	0.022	0.56	0.030	0.76	E60S-1	90	24	1.0	4-5/8	115	625	283.60
22	0.032	0.81	0.030	0.76	E60S-1	120	27	1.2	5	125	730	331.13
20	0.037	0.94	0.030	0.76	E60S-1	120	27	1.2	10-1/8	253	1337	606.46
22	0.032	0.81	0.035	0.89	E60S-1	140	26	1.0	6	150	800	362.88
20	0.037	0.94	0.035	0.89	E60S-1	140	26	1.0	6	150	1147	520.33
18	0.033	0.84	0.035	0.89	E60S-1	190	27	1.0	8-1/2	212	1507	683.58
16	0.059	1.50	0.035	0.89	E60S-1	190	28	2.0	17-1/4	431	1434	641.46
14	0.072	1.82	0.035	0.89	E60S-1	190	28	5.0	40-1/4	1006	2600	1179.96
18	0.039	0.99	0.045	1.14	E60S-1	200	27	0.7	4	100	1414	641.39
16	0.059	1.50	0.045	1.14	E60S-1	260	29	1.0	6	150	2070	938.95
14	0.072	1.82	0.045	1.14	E60S-1	300	30	1.5	12-3/4	319	3224	1462.41
12	0.110	2.79	0.045	1.14	E60S-1	300	30	3.5	28-1/2	712	4300	1950.48
11	0.124	3.15	0.045	1.14	E60S-1	300	30	4.2	34	850	4114	1866.11
16	0.059	1.50	1/16	1.6	E60S-1	250	29	1.0	2-3/4	69	1654	750.25
14	0.072	1.82	1/16	1.6	E60S-1	360	31	1.0	5-1/2	137	3340	1515.02
12	0.110	2.79	1/16	1.6	E60S-1	440	32	1.0	7-1/4	181	5000	2268.00
11	1/8	3.18	1/16	1.6	E60S-1	490	32	1.0	8-1/2	212	5634	2556.58
	5/32	4.0	1/16	1.6	E60S-1	490	32	1.5	9	225	5447	2460.76
	3/16	4.76	1/16	1.6	E60S-1	490	32	2	16-3/4	419	6834	3179.90
	1/4	6.4	1/16	1.6	E60S-1	490	34	3.5	28-1/8	703	8667	4721.35
16	0.062	1.57	3/32	2.4	E70T-2	400	30	0.6	1-3/8	34	2550	1156.68
11	1/8	3.18	3/32	2.4	E70T-2	500	34	0.8	3	75	3400	1442.24
	3/16	4.76	3/32	2.4	E70T-2	650	38	1.6	8-1/4	206	7050	3197.88
	1/4	6.4	3/32	2.4	E70T-2	750	40	2.2	15-3/4	394	10300	4672.08

Note: Contact tip-to-work distance: 1/4 to 3/8 for fine wire, 7/8 for large wire and flux-cored wire, CO_2-7/8 Gasless—1-1/2.

Note: CO_2 when used: 35 cubic feet per hour (6.5 L/M).

assemblies, the attachment of brackets to body assemblies, frame assemblies, the assembly of industrial products, the assembly of lattice structural beams, and for innumerable other applications. The strengths are in the same relationship as resistance spot welds on the same materials in the same thicknesses.

Variations of the Process

There is one variation that would be more accurately described as a plug weld. It is used to join dissimilar metals. It has been used for joining aluminum to copper and glavanized steel to aluminum. Aluminum filler wire is used with inert gas through a hole in the copper or galvanized part. Copper terminals can be joined to aluminum cables and galvanized steel brackets can be joined to aluminum pans.[2] In plug welding it is important to establish the arc on the bottom piece for a good-quality weld.

Another variation of arc spot welding is done with the shielded metal arc welding process using covered electrodes. Special spot welding guns or holders are used. Small-diameter electrodes are used. The special holder causes the arc to strike and holds a short arc for several seconds without manual assistance. An arc shield surrounds the arc area and a welding helmet is not required. This process variation will weld through 16-gauge steel in the flat, horizontal, and vertical positions. It is used primarily in auto body repair shops.

26-2 SHEET METAL WELDING

Sheet metal is metal having a thickness of ⅛ in. (3.2 mm) or less. This usually means that it has a gauge number of 11 and higher, the higher numbers indicating thinner thicknesses of metal. The thickness and gauge number relationship are shown in Figure 26-6. Welding can be performed on the thinnest metal produced but extra special fixturing and automatic travel are required. Under normal conditions using a manual or semiautomatic process sheet metal approximately 0.035 in. (0.9 mm) in thickness or roughly 20 gauge can be welded. Of the gauges shown in Figure 26-6, the Steel Sheets Manufacture Standard is the most commonly used in the United States.

Thin sheets of stainless steels, aluminum alloys, and nickel alloys are also welded. The processes most commonly used are gas metal arc welding for thin sections, and gas tungsten arc and plasma arc welding for the thinnest metals.

There are two major problems involved with the welding of sheet metal: (1) minimizing the distortion, and (2) avoiding burn-through.

The problems of burn-through and distortion can both be minimized by the use of tight fitup, clamping, and aligning fixtures and backup bars. These are all recommended for production welding; however, for maintenance and repair welding the accurate fitup, clamping, and the use of backup bars may not be possible.

Of all the welding processes, the gas metal arc welding process, utilizing the short-circuiting arc transfer, is the most suitable. This process has replaced shielded metal arc welding for almost all sheet metal applications. The main reason for the preference of this process is its ability to operate at a wide range of current levels. Its relative high-speed travel, which balances the heat loss-buildup problem, greatly reduces weld distortion. Brazing is used for galvanized steel applications and for joining copper alloys. The single carbon arc method and the gas torch method are both used but are losing popularity.

The problem of burn-through occurs with many of the processes, and steps to avoid burn-through include the use of close-tolerance cutting to provide tight, even fitup between parts. The preparation of sheet metal for welding is normally by shearing, which produces straight edges that can easily be aligned properly. A backup bar of copper and the ample use of clamps to hold the sheet metal in alignment against the backing bar will aid in making good-quality weld joints. The travel speed should be as high as possible; this is a matter of welder skill and practice. The welder should try to travel at a uniform high speed but must be able to follow the joint accurately.

Fitup and distortion are closely related since distortion ahead of the arc will cause the fitup to vary and this creates the likelihood for burn-through. A large number of small tack welds should be used. They should be relatively short but closely spaced. This will help maintain tight fitup and will reduce weld distortion. It is also helpful to use the push-travel angle when using any of the arc processes. Another assist is to make the weld in a downhill position. If the work can be tilted so that welding can be done downhill, approximately 45°, a flatter bead will result, travel speed will be higher, and this will reduce distortion.

When using the gas metal arc welding process the argon CO_2 mixture (75% argon and 25% CO_2) helps improve the welding operation since it tends to reduce penetration into the joint, reduces the spatter level, and produces a smoother weld bead. The fine wire gas metal arc process can be used at extremely low currents and the current level should match the thickness of the metal being welded. The flux cored arc welding process is not used on thin sheet metal. FCAW with very small electrode wire can be used on the heavier gauges.

When using the shielded metal arc welding process use the the smallest size electrodes possible. This is the $\frac{3}{32}$-in. diameter size or for heavier sheet metal, the ⅛-in. diameter size. Either ac or dc can be used; however, this will dictate the electrode type that should be selected. If ac equipment is available, the E6013 electrodes should

Gauge Number	Aluminum and Brass Brown and Sharp (in.)	Steel Sheets Mfrs. Std.[a] (in.)	Strip and Tubing and Copper Birmingham or Stubs (in.)	Nearest Metric Thickness[b]	Stress Wire Gauge[c]
6/0's	0.5800				0.4615
5/0's	0.5165		0.500		0.4305
4/0's	0.4600		0.454		0.3938
4/0's	0.4096		0.425		0.3625
3/0's	0.3648		0.380	10.0	0.3310
2/0's	0.3249		0.340	9.0	0.3065
1	0.2893		0.300	8.0	0.2830
2	0.2576		0.284	7.0	0.2625
3	0.2294	0.2391	0.259	6.0	0.2437
4	0.2043	0.2242	0.238	5.5	0.2253
5	0.1819	0.2092	0.220	5.0	0.2070
6	0.1620	0.1943	0.203	4.8	0.1920
7	0.1443	0.1793	0.180	4.5	0.1770
8	0.1285	0.1644	0.165	4.2	0.1620
9	0.1144	0.1495	0.148	3.8	0.1483
10	0.1019	0.1345	0.134	3.5	0.1350
11	0.0907	0.1196	0.120	3.0	0.1205
12	0.0808	0.1046	0.109	2.8	0.1055
13	0.0720	0.0897	0.095	2.2	0.0915
14	0.0641	0.0747	0.083	2.0	0.0800
15	0.0571	0.0673	0.072	1.8	0.0720
16	0.0508	0.0598	0.065	1.6	0.0625
17	0.0453	0.0538	0.058	1.4	0.0540
18	0.0403	0.0478	0.049	1.2	0.0475
19	0.0359	0.0418	0.042	1.1	0.0410
20	0.0320	0.0359	0.035	1.0	0.0348
21	0.0285	0.0329	0.032	0.090	0.0317
22	0.0253	0.0299	0.028	0.080	0.0286
23	0.0226	0.0269	0.025	0.070	0.0258
24	0.0201	0.0239	0.022	0.060	0.0230
25	0.0179	0.0209	0.020	0.055	0.0204
26	0.0159	0.0179	0.018	0.045	0.0181
27	0.0142	0.0164	0.016	0.040	0.0173
28	0.0126	0.0149	0.014	0.035	0.0162
29	0.0113	0.0135	0.013		0.0150
30	0.0100	0.0120	0.012		0.0140
31	0.0089	0.0105	0.010		0.0132
32	0.0080	0.0097	0.009		0.0128
33	0.0071	0.0090	0.008		0.0118
34	0.0063	0.0082	0.007		0.0104
35	0.0056	0.0075	0.005		0.0095
36	0.0050	0.0067	0.004		0.0090
37	0.0045	0.0064			0.0085
38	0.0040	0.0060			0.0080

[a] Replaces U.S. standard (revised) gauge.
[b] ANSI B32.3.
[c] Replaces Washburn and Moen gauge.

FIGURE 26-6 Sheet metal gauges.

be used. Ac is preferred over direct current for welding thinner sheet metal. If dc equipment is to be used, the selection would be AWS E6012 electrodes. When using the electrode negative (straight polarity), penetration is reduced and the metal transfer is more of a spray type. A short arc length should be used and the arc length should equal one core wire diameter. The pull travel angle is preferred and the weld joint should be positioned at approximately 45° so that the welding can be done in the downhill direction.

When plasma arc welding or gas tungsten arc welding is employed, use high current and maximum travel speed. The gas tungsten arc process has the slowest travel speed of the arc processes and this tends to increase distortion. The plasma process can be used at a higher speed and this will reduce distortion.

When using the oxyfuel gas welding process, the forehand technique or forward pushing travel angle should be used. When using the single carbon arc process and a bronze rod, the arc is played on the rod and allow-

Welding Process	Sheet Metal Gauge[a] Gauge	in.	mm	Filler Rod or Electrode Diameter in.	mm	Volt	Amperes DC	Shielding Gas and Flow	Travel Speed in./min	mm/min
PAW	25	0.020	0.5	—	—	18	12	20	21	533
	20	0.030	0.8	—	—	18	34	20	17	432
	16	0.062	1.6	—	—	20	65	20	14	355
	3/32	0.093	2.4	—	—	17	85	20	16	406
	1/8	0.125	3.2	—	—	18	100	20	16	406
GTAW	20	0.032	0.8	1/16	1.6	11	75–100	10	13	330
	18	0.040	1.0	1/16	1.6	12	90–120	10	15	380
	16	0.063	1.6	1/16	1.6	11	95–135	10	15	380
	3/32	0.094	2.4	3/32	2.4	12	135–175	10	14	355
	1/8	0.125	3.2	1/8	3.2	12	145–205	12	11	280
GMAW	24	0.025	0.6	0.030	0.8	16	30–50	20	16	406
	22	0.031	0.8	0.030	0.8	16	40–60	20	19	482
	20	0.037	0.9	0.035	0.9	17	55–85	20	37	940
	18	0.050	1.3	0.035	0.9	18	70–100	20	37	940
	16	0.063	1.6	0.035	0.9	18	80–110	20	32	813
	5/64	0.078	1.9	0.035	0.9	19	100–130	20	27	686
	1/8	0.125	3.2	0.035	0.9	20	120–160	20	20	508
SMAW	24	0.025	0.1	3/32	2.4	25	40	—	20	508
	22	0.031	0.8	3/32	2.4	25	40	—	21	533
	20	0.038	0.9	3/32	2.4	25	50	—	28	711
	18	0.050	1.3	3/32	2.4	27	65	—	30	762
	16	0.063	1.6	3/32	2.4	27	75	—	30	762
	5/64	0.078	1.9	3/32	2.4	28	100	—	35	889
	1/8	0.125	3.2	1/8	3.2	26	120	—	40	1016
CAW[b]	24	0.025	0.1	3/16	4.8	18	25	—	8	203
	22	0.031	0.8	3/16	4.8	18	35	—	8	203
	20	0.038	0.9	3/16	4.8	18	45	—	10	255
	18	0.050	1.3	3/16	4.8	19	50	—	10	255
	16	0.062	1.6	3/16	4.8	20	50	—	12	305
	5/64	0.078	1.9	1/4	6.4	20	80	—	13	330
	1/8	0.125	3.2	1/4	6.4	19	95	—	15	380

[a]Parameters are suitable for square groove butt or for fillet welds.
[b]Bronze cold wire (1/8 in. 3.2 mm) used with carbon arc welding.

FIGURE 26-7 Sheet metal welding schedules.

ed to melt onto the sheet metal joint. This reduces heat into the joint, reduces distortion, and allows for rapid travel speed. The electrode or filler rod must be selected to match the base metal. Procedure information using these processes is given in Figure 26-7.

26-3 ONE-SIDE WELDING

The term *one-side welding* has become very popular in the welding industry in the last few years. One-side welding is not new, but it has been popularized and given a high degree of importance in the shipyards. One-side welding is the production of a butt weld from one side of the joint that achieves a 100% efficiency and produces a back side of the joint that is acceptable from an appearance and quality viewpoint.

All welds made on medium- and small-diameter pipe and tubes are one-side welds, since the back side of the weld is inaccessible. During the early days of submerged arc welding, techniques for backing the joint with flux were developed and produced welds made entirely from the top side of the joint. Why then is there so much interest now in one-side welding?

In the shipbuilding industry, it is customary to handle very large welded subassemblies. Previously, automatic welding was done by a single pass from each side of the joint. This required the assemblies to be turned over to complete the weld. Turning large assemblies involved extremely heavy capacity overhead cranes with sufficient height. Heavy-capacity cranes and high bays in buildings are extremely expensive. The elimination of the turning-over operation represented a substantial cost savings in the building of large ships. There is another advantage of welding from one side. It would fit in with the use of automatic conveyors and material-moving systems for better assembly-line shipbuilding.[3]

One-side welding can be divided into two different methods of operation. The first method uses a weld-backing apparatus. Flat plates are set on this apparatus and long straight joints are automatically welded in the flat position. The second method uses portable backing materials that are taken to and applied to the back side of the weld joint, wherever it is located.

With one-side welding it is difficult to obtain a 100% joint efficiency over the entire length of the joint. Welds made from both sides usually have an overlap of penetration. The extent of this overlap is not important as long as the overlap occurs. The problem of joining large assemblies is complicated by the material preparation tolerances. The alignment and flatness and warpage inherent to any welding operation create fitup problems of large subassemblies. The variations of fitup rapidly change the penetration of the weld and the reinforcement on the back side of the weld joint.

Another problem of welding large structures is the straightness or fairness of the parts at the joint. Misalignment is very common and complicates the problem of welding. These problems can be eliminated with one-side welding.

One method of making one-side welds was developed during the early use of submerged arc welding. This method utilized submerged arc flux on the underside of the weld joint. The flux was brought into intimate contact with the back of the joint by means of air pressure in a hose. This system has been called the FB method, which indicates "flux backing" (Figure 26-8).

Another method used in seam welding machines is

FIGURE 26-8 Backing flux (BF) method.

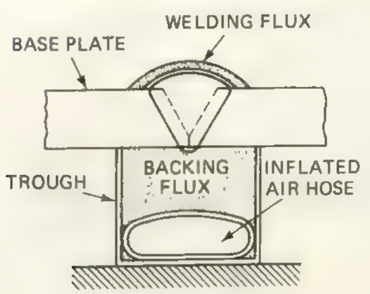
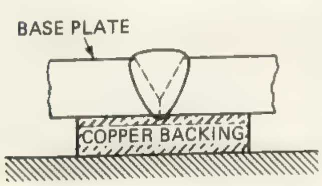


FIGURE 26-9 Copper backing (CB) method.



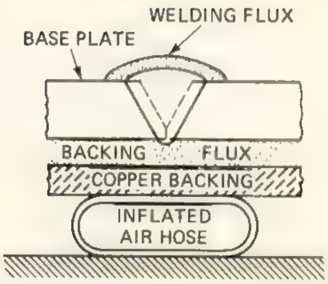


FIGURE 26-10 Flux copper backing (FCB) method.

known as the "copper backing" method, indicated by the letters CB (Figure 26-9). This has been used for many arc welding processes. The copper backing method utilized heavy copper bars brought into intimate contact to the back side of the weld joint. Often a recessed groove is placed in the copper bar immediately below the weld joint to allow for root penetration. For heavy-duty welding the copper bar would be water cooled. For high-quality work on nonferrous metals using gas metal arc welding, backing gas was introduced into the recessed groove.

Both of these methods were highly successful for thinner materials or for relatively short welds. For heavier plates, or for long joints, neither of these methods was entirely satisfactory. A development combining the advantages of both while eliminating their disadvantages is known as the "flux-copper backing" method, abbreviated FCB (Figure 26-10). This backing method uses a layer of granulated flux of consistent thickness in contact with the underside of both workpieces and in contact with the upper side of a copper backing bar. The copper backing bar helps control the uniform size of the reinforcement bead. The Japanese have a word, *Uranami*, which describes the root bead viewed from the back side of the joint. The width of the flux layer is approximately 4 in. (100 mm), which will accomodate normal variation of the joint. The copper bar is approximately ½ in. (12.5 mm) thick and 5 in. (125 mm) wide and as long as the joint. The thickness of the backing flux is about ¼ in. (6 mm). The backing flux and the welding flux are normally the same flux. Special backing flux may be used. The back pressure keeps the flux in intimate contact with the parts being welded.

There are variations to all three of these methods. For example, with the flux backing (FB) method, sometimes the flux is encased in a paper container, which is burned during the welding operation. This makes the fitup quicker. In the case of the copper backing (CB) method, different kinds of coatings are placed on the copper bar. Some users place fiberglass tape or other inorganic fibers on the copper bar to maintain pressure

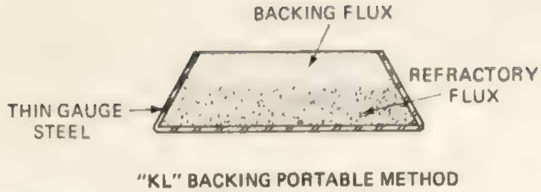


FIGURE 26-11 Portable (KL) backing method.

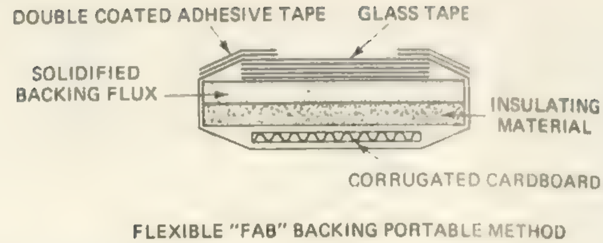


FIGURE 26-12 Portable flexible (FAB) backing method.

against the back side of the weld. In the flux copper backing (FCB) method, different systems are used to keep the backing against the work and different types of flux are used.

An improvement of the FB method utilizes special backing flux, called RF for "refractory flux." This flux helps to form a uniform backing or uranami bead. The flux contains phenol resin binders which undergo thermal hardening from the heat of the arc.

The second type of one-side welding utilizes portable backing material applied to the back side of the joint. The portable system uses short lengths of assemblies containing the backing materials. One of these, known as the KL method, is shown in Figure 26-11. This backing assembly is approximately 2 ft long. The top layer of flux is the bead-forming type, underneath which is a solid refractory material. Both are enclosed in a thin sheet metal trough. This steel trough is sufficiently flexible so that it can be formed to fit the changing contour of a ship structure.

Another portable method utilized the FAB backing assembly (Figure 26-12). This assembly is composed of several layers of fiberglass tape, under this is a layer of insulating material, and below this is a corrugated cardboard pad. This entire assembly is enclosed in a cardboard container, which holds double-coated adhesive tape used to keep the backing assembly in intimate contact with the underside of the weld joint. This assembly is relatively flexible and can be formed to the contour of the part being welded.

There are several other configurations of portable backing devices. One of particular interest is known as the CRB method, for "coated rod backing." It is similar to a large covered electrode except that the flux covering on the rod does not melt. When the root opening is excessive, two rods may be used. Magnetic clamps are used to hold the backing assembly in place.

A popular portable backing system utilizes an adhesive tape which carries a layer of backing flux along with several layers of aluminum foil. This backing tape can be placed against the underside of the joint and will adhere to the parts. The flux will help form the backing bead. Tape is being used with the consumable electrode arc welding process. When using submerged arc welding, sufficient root face must be provided so that the welding arc does not come in contact with the backing flux in the tape. Figure 26-13 shows this tape with the flux. Figure 26-14 shows the tape in use joining cylindrical members. The tape is on the outside of the structure, which is the root side of the joint (Figure 26-15). The weld is made from inside with a mechanized submerged arc welding head.

This tape is very helpful for welding vertical joints using the gas metal arc process. The tape eliminates the draft of air blowing through the root opening, which reduces the efficiency of the shielding gas.

FIGURE 26-13 Backing tape with flux.

FIGURE 26-14 Backing tape in use, back side.

FIGURE 26-15 Making the submerged arc weld.

26-4 NARROW GAP WELDING

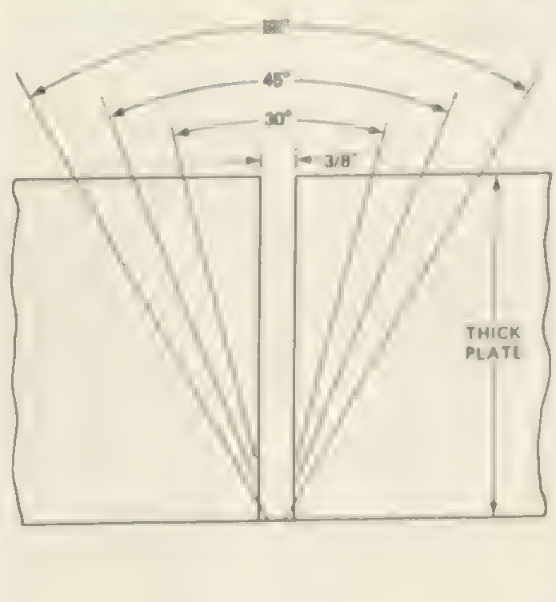
Narrow gap welding (NGW) is a term applied to arc welds made in thick materials utilizing a square groove weld joint or a V-groove weld joint with a groove angle of not over 10° and utilizing a root opening or gap between the parts ¼ in. (6.4 mm) to ⅜ in. (9.5 mm) wide.[4] Narrow gap welding has been used on material from 2 in. (50 mm) thick up through 12 in. (300 mm) thick. A backing system or a U-groove design is required at the root.

For economic reasons, international attention is being directed toward narrow gap welding. Heavier plates are being used for manufacturing pressure vessels, nuclear reactors, penstocks, ship decking, and so on. As the thickness increases, the amount of weld metal in the joint increases at a much greater rate. Figure 26-16 shows the cross-sectional area of narrow gap square groove design versus the single-V-groove design with an included groove angle of 30°, 45°, or 60°. The narrow gap welding concept can also be used for welding heavy-wall pipe and tubing. This can be accomplished rolling the pipe in the 1G position or orbiting the pipe in the 5G position. The cross-sectional view of a narrow gap weld is shown in Figure 26-17.

The economic advantage is obtained when welding plate thicknesses of 1½ in. (38 mm) and above and is based on using less weld metal to produce the joint, which in turn decreases the labor cost.[5]

The advantages of narrow gap welding over conventional welding include the following:

FIGURE 26-16 Comparison of cross-sectional area.



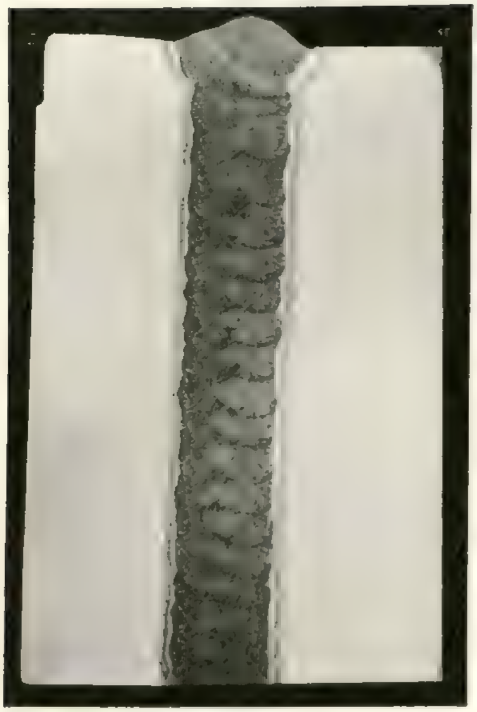


FIGURE 26-17 Cross section of narrow gap weld.

1. High-quality welds, the result of low heat input and the multipass technique, which provides an extremely narrow heat-affected zone and fine-grained weld metal. The mechanical properties of the weld joint are excellent.
2. High productivity as a result of smaller cross section of the weld. This uses less weld metal and less labor for joint preparation and welding operations.
3. All-position capability, due to the small volume of the molten weld pool and low heat input.
4. Lower residual stresses, due to the smaller number of weld passes to produce the joint.

Narrow gap welding is not a welding process. It can utilize several arc welding processes. The most popular use for narrow gap welding is gas metal arc welding using the spray transfer mode. Narrow gap welds can also be made with flux-cored arc welding using special flux-cored electrodes. Submerged arc welding has also been used for making narrow gap welds. Gas tungsten arc welding with the hot wire version can also be used for narrow gap welding.

It is possible to consider electrogas welding and electroslag welding as narrow gap processes since they both employ square groove welds with a relatively small root opening on heavy plate materials. However, these are not included in this section.

Narrow gap welding can be done on carbon steels, on low-alloy high-strength steels, and on both quenched and tempered steels. The low heat input makes it particularly advantageous for welding quenched and tempered steels.

There are disadvantages to narrow gap welding, including:

1. Repair welding is difficult and must be done by conventional techniques.
2. The welding head and control are relatively complex and expensive.
3. Joint fitup must be accurate in order to have consistent results the entire length of the joint.
4. Magnetic arc blow can be a problem with gas metal arc welding.
5. Technology is more demanding, which requires better-trained operators.
6. Filler metals required are special and may be more expensive.

Most of the work on narrow gap welding has been done with gas metal arc welding, but a variety of techniques has been developed.

The original narrow gap work involved two welding arcs, two electrode wires, and two contact tubes. One is directed toward one sidewall and the other toward the opposite sidewall. The wire feeders, contact tubes, and so on, are mounted on a special carriage with a fixed distance between them and the sidewalls. This ensures proper sidewall fusion, regardless of minor variations in the root opening. The shielding gas is introduced into the joint by special nozzles which extend to the bottom of the groove. A backing strip is used for making the first, and usually the second pass. Subsequent passes are deposited on previous layers. Approximately 10 weld passes are required for each in. (25-mm) of joint thickness. Typical welding conditions would utilize an electrode diameter of either 0.035 in. (0.9 mm) or 0.045 in. (1.1 mm). The current would be in the neighborhood of 225 to 250 A dc electrode positive at 25 to 26 V. Constant-voltage power sources are used. The travel speed would be from 40 to 50 in./min. (1000 to 1200 mm/min), and the shielding gas could be 75% argon plus 25% CO_2 or 95% argon and 5% oxygen. The head is arranged so that the contact tubes are approximately ½ in. above the arc. Contact tubes are retracted as the weld is made. The major factor of this technique is the necessity to direct the electrode wire to the joint sidewall. This is done by introducing "cast" into the electrode wire immediately before it goes into the contact tube. This ensures that as the electrode wire leaves the contact tube, it will travel to the side to which it is directed. In this way sidewall penetration is maintained and undercut is avoided. The entire head assembly must be accurately built, properly insulated, and adjustable for variations in gap and allowances made as the weld build up. The

control system is designed to provide automatic sequence to start and stop the electrodes at the same location in the joint. The major problem is directing the electrode wires into the sidewall to avoid undercutting and potential defects.

Another system utilizing gas metal arc welding is the "Kobe twist wire" technique. The electrode is actually two wires twisted together. This system uses a straight contact tube, and as the electrode melts, two arcs are generated from the tips of the two wires. They have a straight transfer mode into the sidewall and provide continuous rotational movement. The rate of arc rotation depends on the pitch of the twisted electrode wires and on the arc length. This technique achieves good sidewall penetration.

Another gas arc metal variation uses an oscillating or swinging torch or a swiveling torch. Another method uses a contact tip bent at the end. One of the most novel systems uses a rotating contact tip where the electrode is off-center of the axis of rotation. This is known as the "Nippon Kokon rotating arc" technique. Other systems use preformed wire, bent wire, and so on.

Another slightly different system uses a wider root gap, 1½ times larger, and uses a larger electrode wire, normally ⅛ in. (3.2 mm) in diameter. The welding current ranges from 400 to 450 A, and the voltage ranges from 30 to 37 V with the electrode negative. Shielding gas composed of one-third CO_2, one-third argon, and one-third helium is used. The contact tube is farther away from the arc and with straight polarity seems to help direct the electrode wire to the sidewalls for complete fusion. A backing strip is used for the first pass. Metal transfer is globular, but the spread of the arc is sufficient to make a pass as wide as the groove. An 18° drag angle of the electrode wire is used. Heat input is greater with this method.

New variations of gas metal arc welding are still appearing for narrow gap welding. The latest narrow gap system comes from Canada. It utilizes two electrode wires feeding simultaneously but directed to opposite sides of the joint. Sidewall fusion is excellent and variations of the root opening, within broad limits, are accommodated. The special feature of this method is the use of two power sources using pulsed current. The peak current pulse alternates from one electrode to the other and avoids the arc disturbance that normally occurs when two arcs are feeding the same weld pool. The control circuit automatically changes welding parameters to accommodate variations in the root opening.

One of the problems with gas metal arc welding and narrow gap welding is arc blow and the loss of arc stability. It is possible to overcome interaction of the two arcs by pulsing the two power sources with the proper program.

Special flux-cored or metal-cored electrode wires have been developed for narrow gap welding. These are used in the same manner as solid wires with gas metal arc welding.

The submerged arc welding process is also used for narrow gap welding. Submerged arc welding employs ac current, which avoids the magnetic arc blow problem. Larger electrode wires are normally used. Higher heat input and greater deposition rates are also employed. Special submerged arc flux is used to avoid slag entrapment.

The gas tungsten arc welding process with a "hot" filler wire is used for narrow gap welding. This version provides good arc stability, good out-of-position capability, good sidewall penetration, and no spatter and slag. The deposition rates are lower, and for this reason the method is used on only certain applications. A special head containing the tungsten electrode provides for arc oscillation and carries the filler wire to the arc. This process has not been used on extremely thick materials.

Undoubtedly, additional variations of the arc welding processes will be developed to provide the economic and quality advantages of narrow gap welding.

26-5 UNDERWATER WELDING

Underwater welding began during World War I, when the British Navy used it to make temporary repairs on battle ships. These repairs consisted of welding around leaking rivets on the ships hulls. The introduction of covered electrodes made it possible to weld under water and to produce welds having approximately 80% of the strength and 40% of the ductility of welds made in air. Underwater welding was originally restricted to salvage operations and emergency repair work, and was limited to depths below the surface of not over 30 ft (10 m). Major advances have been made in underwater welding in recent years.

Underwater welding can be subdivided into two major categories: welding in a wet environment and welding in a dry environment. Welding in the wet is used primarily for emergency repairs or salvage operations in relatively shallow water.

Wet Welding

The poor quality of welds made in the wet is due to the problem of heat transfer, welder visibility, and the presence of hydrogen in the arc atmosphere. When the base metal and the arc area are surrounded entirely by water, there is no temperature or heat buildup of the base metal at the weld. This creates a high-temperature gradient or quench effect, which reduces the quality of the weld metal. The arc area is composed of a high concentration of water vapor. The arc atmosphere of hydrogen and oxygen of the water vapor is absorbed in the molten weld metal and contributes to porosity and hydrogen cracking. In addition, welders working under

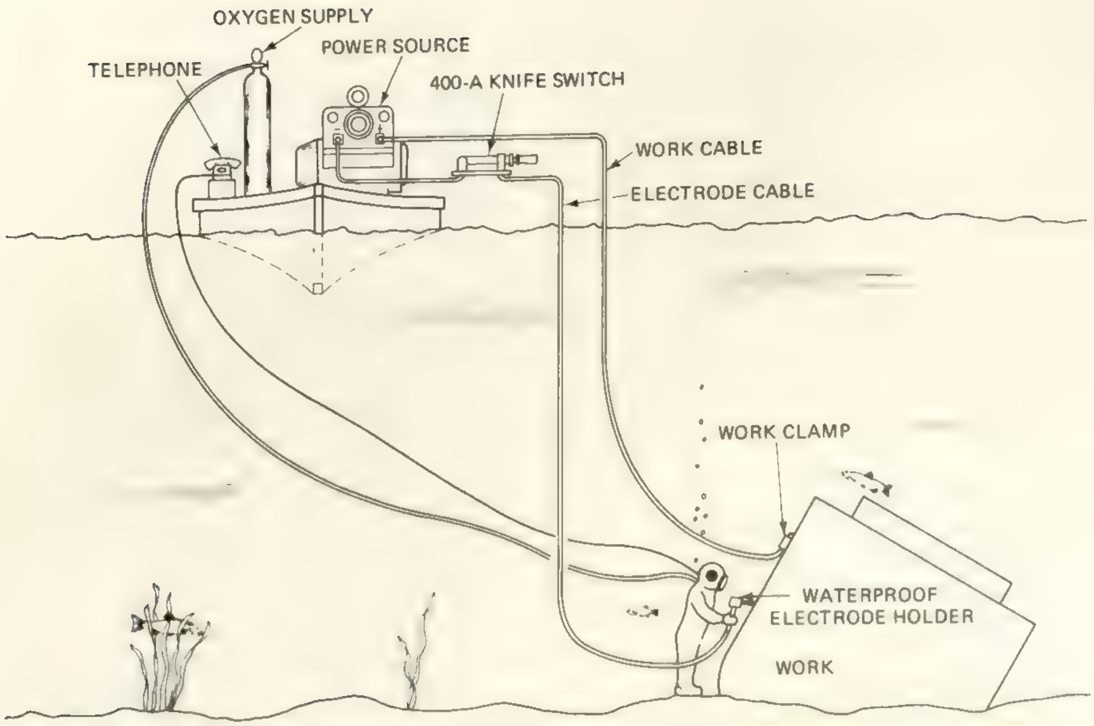


FIGURE 26-18 Arrangements for underwater welding in the wet.

water are restricted in their efforts to see and manipulate the welding arc. Under ideal conditions, the welds produced in the wet with covered electrodes are marginal. They may be used for short periods but should be relaced with good-quality welds as quickly as possible. Improvements in underwater welding electrodes are improving in-the-wet weld quality.

Efforts have been made to produce a bubble of gas in which the weld can be made. This technique has not been able to ensure good-quality welds made with covered electrodes in-the-wet.

The general arrangements for underwater in-the-wet welding are shown in Figure 26-18. The power source for underwater welding should always be a direct-current machine rated at 300 or 400 A. Motor generator welding machines are often employed for underwater welding in-the-wet. The frame of the welding machine must be connected to the ship. The welding circuit must include a positive switch, usually a knife switch that is operated on the surface upon the command of the welder-diver. The knife switch in the electrode circuit must be capable of breaking the full welding current. It is required for safety reasons. The welding power should be connected to the electrode holder only while the welder is welding. Direct current with electrode negative (straight polarity) is used. Special electrode holders with insulation against the water are employed (Figure 26-19). The underwater welding electrode holder will accommodate two sizes of electrodes, normally $\frac{3}{16}$ in. (4.8 mm) and $\frac{5}{32}$ in. (4 mm). The electrode types normally used meet the AWS E6013 classification, and must be waterproofed. This is done by wrapping them with waterproof tape or by dipping them in a sodium silicate mix or other waterproofing material. Commerical electrodes for underwater welding are available.

The welding lead and work lead should be at least $\frac{2}{0}$ size, and the insulation must be perfect. If the total length of the lead exceeds 300 ft (100 m), they should be paralleled. With paralleled leads to the electrode holder the last 3 ft (1 m) should be a single cable. All connec-

FIGURE 26-19 Underwater electrode holders.

tions must be thoroughtly insulated so that the water cannot come in contact with the metal parts. If the insulation leaks, the seawater will contact the metal conductor and part of the current will leak away and will not be available at the arc. In addition, there will be rapid deterioration of the copper cable at the leak. The workpiece lead should be connected to the work being welded within 3 ft (1 m) of the point of welding. Welding in the wet is shown in Figure 26-20.

A special underwater cutting torch which utilizes the oxygen arc cutting process using tubular steel covered electrodes is also shown by Figure 26-19. This torch is fully insulated and utilizes a twist-type collet for gripping the electrode. It includes an oxygen valve and connections for attaching the welding lead and an oxygen hose. It is equipped to handle up to 5/16-in. (7.9-mm) tubular electrode. In this process the arc is struck in the normal fashion and oxygen is fed through the center hole of the electrode to provide the cutting action. The same electrical connections mentioned above are employed.

Complete information concerning underwater cutting and welding in-the-wet with covered electrodes is given by the U.S. Navy's "Underwater Cutting and Welding" Technical Manual.[6]

The need to produce high-quality welds under water has increased as oil and gas are found in deep water. Most offshore exploration, drilling, and production, until recently, was in water ranging from 30 to 50 ft. (10 to 16 m) deep. When a pipeline needs to be repaired, it is raised to the surface, repaired, and lowered back to the ocean floor. Exploration, drilling, and production are moving into deeper water, up to the 1000 ft (305 M) depth. Modifications and work must be done on the ocean floor. More pipelines are damaged and there is a necessity for making tie-ins of subsea pipelines on the ocean floor. The repairs and tie-ins must be high-quality welds to prohibit possibility of leaks or oil spills. This type of work is now being done in depths of 200 to 600 ft. (61 to 182 m).

FIGURE 26-20 Welding in the wet.

Dry Welding

The development of welding in-the-dry or in a dry environment make it possible to produce high-quality weld joints that meet x-ray and code requirements. A number of welding processes are currently used for welding in-the-dry: the shielded metal arc, the gas tungsten arc, the plasma arc, the gas metal arc, and the flux-cored arc welding process. The shielded metal arc welding process is rarely used for welding in-the-dry environment, because of the large amount of smoke and fumes produced. When covered electrodes are used, an extensive air moving, filtering, and refrigeration system must be employed. The gas tungsten arc welding process is being used to produce welds that meet the quality requirements of API standard 1104. It is being used at depths of over 300 ft (91 m). The gas tungsten arc welding process is a relatively slow welding process, but it is acceptable since the welding operation is a small part of the total repair operation.

Efforts are ongoing to develop plasma arc welding more fully for deep-water operations. Successful application of gas metal arc welding in-the-dry has been made to depths as great as 180 ft (51 m).

There are two basic types of in-the-dry underwater welding. One involves a welding chamber or habitat and is known as hyperbaric welding. The habitat or large welding chamber provides the welder-diver with all the necessary equipment for welding and related work in a dry environment. The weld chamber is made so that it can be sealed to the part to be welded. Since most of this work is on pipe, arrangements are made to seal the habitat to the pipe. The bottom of the chamber is exposed to open water and is covered by a grating. The pressure of the atmosphere inside the chamber is equal to the water pressure at the operating depth. Figure 26-21 shows a welding habitat.

Life-support equipment involves two-way telephone, video camera for continuous observation, life-support atmosphere for the welder-diver (which may be different from the welding atmosphere), power for tools and for welding, and the gas supply for the welding atmosphere. Habitats usually include an atmosphere-conditioning system used to both cool and filter the atmosphere in the chamber. Filtering is important since metal vapor is released during welding. Air conditioning is employed since heat is generated by welding. For gas metal arc welding the welding power source is normally on the surface. Welding cables are lowered to the habitat to provide power for the arc. The electrode wire and wire feeder and control unit are located in the habitat. The wire feeder must be protected from the high-pressure and high-humidity conditions in the chamber. The electrode wire must also be protected from the humidity.

The gas for breathing and for welding is designed for use at the high pressures which are involved. The pressure in the habitat increases 1 atmosphere or 14.7

FIGURE 26-21 Underwater pressurized habitat for pipe welding.

lb/in.^{2} (1 kg/cm^2) for each 33 ft (10 m) of depth. The water pressure must be equalized by the pressure of the atmosphere within the habitat. This high pressure creates problems for the crew and for welding. With shielded metal arc welding, the problem involves the removal and filtering the atmosphere in the habitat. With gas tungsten arc welding, very little smoke and fumes are generated, but the inert gas used for welding disrupts the breathing atmosphere. For saturated diving work the breathing atmosphere of the welder-diver is based on the working depth. Premixed gas is used and the oxygen content is based on the depth.(7)

Welding with the gas metal arc in a habitat presents specific problems.(8) In shallow depths the welding in the habitat is essentially the same as welding on the surface. When welding at depths of 125 ft (35 m), the pressure is about 4 atmospheres (approximately 50 psi gauge). The weld metal quality is essentially the same as surface made welds; however, the welding voltage increases and weld bead penetration increases. As the depth is increased, the atmospheric pressure increases and the arc becomes more constricted, and this leads to increased arc voltage and increased penetration and higher burn-off rates. This makes the weld pool difficult to handle. At depths beyond 125 ft (35 m) the weld pool becomes increasingly difficult to control and an increased amount of smoke is generated. Special welding power sources are required.

Wet-Dry Welding

Improvements have been made to provide more flexibility for gas metal arc welding when welding underwater.(9) The dry hyperbaric chambers or habitats are extremely expensive and must be designed for specific applications. It is now possible to take gas metal arc welding outside the habitat by the use of special nozzles or chambers which surround the torch. In using this apparatus the welder-diver is in-the-wet or in the water, but the nozzle of the welding gun and material to be welded is in the dry atmosphere (Firgure 26-22). The gun and nozzle are in this small chamber, but the wire feeder and the electrode wire supply are in another watertight pressurized enclosure. The pressure of the shielding gas coming through the system is greater than the pressure of the water at the operating level. The gas flows through the wire feeder enclosure through the electrode conduit to the torch, where it provides the shielding atmosphere for welding. It also provides the pressure to evacuate the small chamber to provide a dry atmosphere. The dry gas environment chambers are relatively inexpensive, small, and lightweight. They are provided with flexible seals to be used against the part being welded. They can be hand-held or made with clamps for quick attachment to the part to be welded. The gun is hand manipulated inside the small chamber, in the same way as on the surface. The chambers are made of transparent material or have sufficient number of windows so that the welder can see inside to properly manipulate and direct the welding arc.

FIGURE 26-22 Welder in the wet welding in the dry with small gas-filled enclosure.

This technique can be utilized for welding with gas metal arc up to 125 ft (35 m) below the surface. High-quality welds can be produced that meet code requirements.

Special safety precautions must be followed when doing underwater welding. These include all precautions normally employed by divers, plus those required for welding. Welder-divers must be aware of the possibilities of entrapped gases in parts being welded or cut. These gases are usually rich in hydrogen and oxygen and may explode when ignited. Only experienced, well-trained personnel should do underwater welding.

26-6 MICROJOINING

Microjoining has not been defined by AWS. From a practical point of view, however, it involves the welding of thin sheet metal up to 0.020 in. (0.5 mm) thick and wire or tubular components up to 0.040 in. (1 mm) in diameter. Microjoining is most widely used by the electronics, instrument, and packaging industries. Some of the common applications are attaching leads to microchips, attaching leads to electronic devices, packaging microchips, making medical instruments and devices such as heart pacers, and packaging these devices and other miniaturized welding applications.[10]

Many of the welding and joining processes described previously are used for microjoining. This includes several arc welding processes, gas tungsten arc, plasma arc, and stud welding. It also includes the laser beam and electron beam welding processes and several of the resistance welding processes. The solid-state processes are employed, including ultrasonic, pressure welding, and diffusion bonding. Soldering and brazing are both widely used. In addition, for certain applications adhesive bonding is employed.

The objective of microjoining is to produce a strong metallurgical joint between the two parts being welded with good electrical conductivity except when adhesive bonding is used to join metals to non-metals.

The materials being microjoined include all the common metals plus exotic and precious metals utilized by the electronics industry. The most common metals welded are copper, aluminum, berilium copper, and silver. The nonmetals include ceramics and plastics.

Microjoining is normally done automatically or with automated equipment. For the larger parts, manual or semiautomatic welding may be accomplished, usually under a magnifying glass with micrometer adjustments for location or movement of parts.

Microjoining requires miniaturized, specialized equipment. High-quality welds are demanded of microjoining since the weld is a part of life-support equipment, delicate computer equipment, and so on.

One of the major applications for microjoining is known as wire bonding. This is the joining of small wires in electro connections between chips and lead frames. Wires as small as the human hair are joined for this application. Components of this type are subject to vibration, shock loading, low temperatures, and high temperatures. Stresses due to vibrations, shock, and temperature changes of different materials require good-quality welds that are strong and have high conductivity.

The arc welding processes mentioned previously use miniaturized equipment, sometimes called micro plasma or miniature TIG. Welding currents range from ½ to 10 A, and pulsed current is normally used. Precision motion and holding devices must be employed, as well as automatic control systems, which are often driven by a microprocessor.

The high-energy beam processes, EB and laser beam welding, are commonly used with lower-powered equipment. Precision motion devices, focusing equipment, and computer controls are required. Special miniaturized resistance welding equipment is widely used. This includes spot welding, projection welding, roll seam and intermittent welding, and ultrasonic welding done with precision motion devices and accurate control systems.

Brazing and soldering utilize capillary attraction, but have precision holding devices and precision methods for introducing fluxes and filler material. The method of heating is essentially the same as with large applications. Electric radiant lamps and the flame are often used. Some work is done in a vacuum or with protective gases. Iron soldering is not practiced.

For adhesive bonding, miniaturized adhesive applicators are required. Microjoining is a rapidly changing technology driven primarily by the electronics industry.

26-7 DABBER WELDING

The Dabber welding method has developed for the precise placement of weld metal on thin edges. It is being utilized for rebuilding knife-edge seals and blades for jet engines. It is shown in operation in Figure 26-23.[11]

Before the development of this method, attempts to repair jet engine parts had been made using different variations of the gas tungsten arc welding (GTAW) process. Gas tungsten arc welding with an automatic wire feed did not produce the desired results. Pulsing the welding current, pulsing travel speed, or pulsing the cold wire feed speed does not produce uniform deposits. Manual welding did provide the proper bead shape but could not be maintained completely around the seal due to welder fatigue. Starts and stops created warpage, which either ruined the part or required excessive machining.

The Dabber method uses a coordinate oscillation motion of the cold filler wire end and the welding torch, which varies the arc length. Dabber welding is designed to automatically rebuild thin edges by depositing narrow

FIGURE 26-23 Making dabber weld.

weld beads one on top of the other. A cross section of a Dabber weld is shown in Figure 26-24.

Dabber welding is an automatic method to duplicate the motions of a manual welder. To understand the Dabber operation, refer to Figure 26-25. Simply stated, as the end of the filler wire dabs into the arc, it cools the weld puddle, and when retracted, it in turn is cooled. The end of the dabbed filler wire, shown in sequence top to bottom on the left, approaches the arc rapidly [1 in. (25 mm) per second]. In normal automatic GTAW the continuously fed filler wire approaches slowly [0.05 in. (1.3 mm) per second]. The end of the filler wire heats as it approaches the arc, melts prematurely, and forms a glob whose size and behavior are unpredictable. This is shown by the right-hand series of drawings. The glob or ball on the end of the filler wire is deposited on the thin edge and produces a high-low deposit which is unacceptable. Multiple bead buildup is nonuniform and not acceptable for seal repair. The use of a higher feed rate does not eliminate the globbing problem. Feeding the filler wire in at a low angle with heat-transfer contact with the base metal helps but does not provide uniform high-quality welds. With the Dabber method, constraints to filler wire

FIGURE 26-24 Cross section of welded seal buildup.

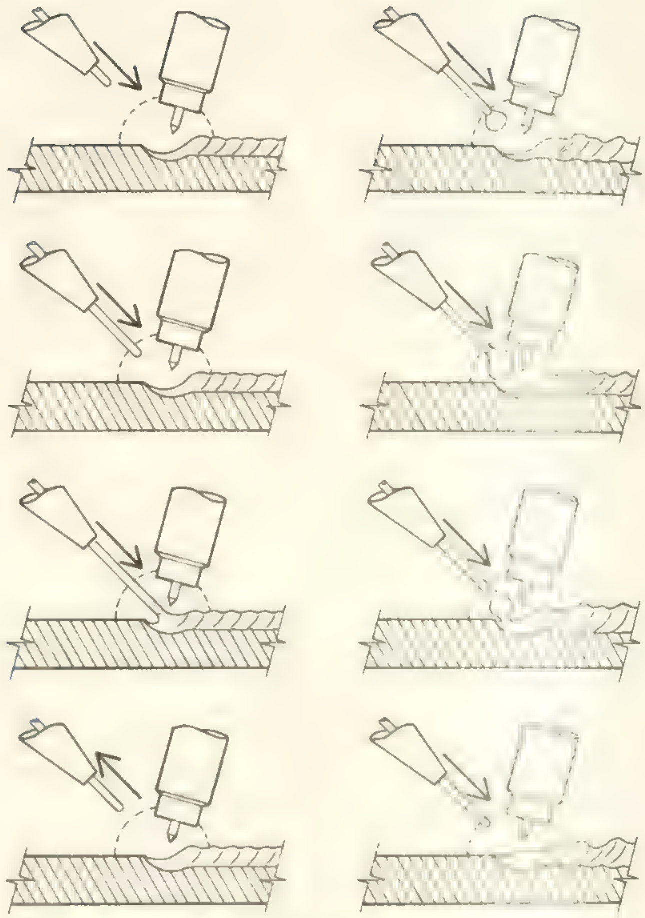


FIGURE 26-25 Dabbing operation.

size and orientation are reduced. The dabbing stroke length is sufficient to pull the end of the heated filler wire, from which a droplet has just been detached while in the fully extended dab position, back quickly. This removes it from the heat of the arc and into the cool copper wire guide nozzle. At the same time the torch moves toward the work and the arc is shortened. The end of the wire reapproaches the arc, at a speed sufficient to prevent "premelting" with associated large glob formation, and melts and deposits another small portion of metal. At this time the arc is lengthened. The amount of weld metal deposited depends on the specific welding parameters. This action is similar to that of an individual doing manual welding. The dabbing action is synchronized with pulsing of the weld current for some applications.

The Dabber method produces a uniform, narrow weld bead with greatly reduced heat input, precise deposition of the filler metal, and repeatability. The regulated heat input controls the penetration of the weld metal so that the composition of the weld metal and the fusion zone is compatible with the original base metal. The heat-affected zone is minimized and postweld heat treatment is rarely required. Warpage is greatly reduced, which reduces the machining time required. It increases productivity, eliminates operator fatigue, minimizes rework, and

reduces the cost of filler metal wire since a larger diameter is used. This improves the surface-to-volume relationship especially important for many alloys. It is used to weld titanium, and nickel alloys such as Inconels, Waspalloys, and Hastelloys. Any type of filler metal that is available in wire form can be used. The Dabber method can also utilize the plasma arc welding process. The complete integrated system, consisting of matched components, is shown in Figure 26-26.

The weld head assembly has many adjustments in order to precisely locate the torch and cold wire feed over different shaped parts. The head can be mounted on a cross beam-carriage with a rotary positioner located beneath it. It can also be mounted on a single frame support with computer-controlled motion of several axes.

The method is used on other repair work for jet engines, turbine blade tips, vanes, and impeller wheel leading edges and blades. The Dabber method is suitable for any application that requires a narrow weld bead to be placed on a thin edge. It is used to salvage rotary saw blades, valve seats, milling cutters, large drill bits, mower blades, dies, and gears. In these applications, the deposited metal surface provides material that gives better wear properties than those of the original material.

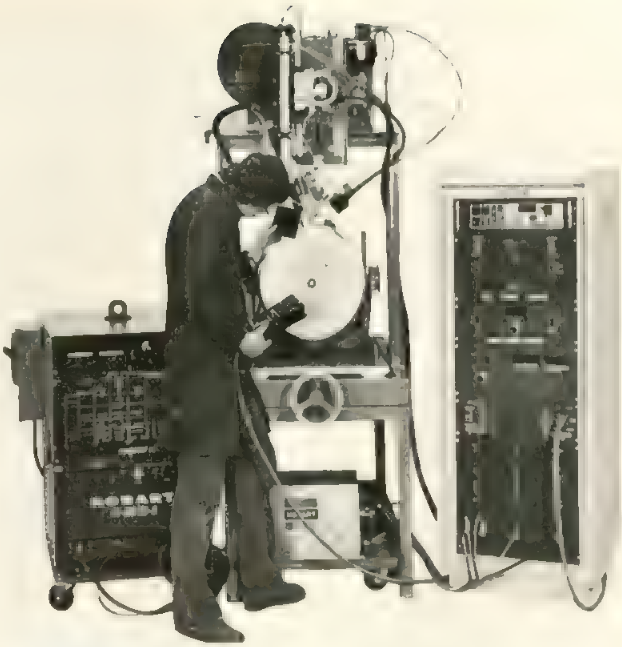


FIGURE 26-26 Dabber welding equipment.

QUESTIONS

26-1. Why is a timer used for arc spot welding?

26-2. Is it necessary to wear a welding helmet when arc spot welding?

26-3. Can arc spot welding be used to join aluminum?

26-4. Can flux-cored arc welding be used for arc spot welding?

26-5. What process is recommended for steel sheet metal welding?

26-6. Why is good fixturing needed for thin sheet metal welding?

26-7. What is one-sided welding?

26-8. Describe two different backing methods.

26-9. Why is one-sided welding important in shipbuilding?

26-10. What are the primary advantages for narrow gap welding?

26-11. What design of weld joint is used for narrow gap welding?

26-12. What welding processes are used for narrow gap welding?

25-13. What is special about underwater welding electrode welders?

26-14. Explain the difference between underwater wet welding and dry welding.

26-15. Can pipe welds be made under water to meet code requirements?

26-16. What is welding in a habitat?

26-17. What determines the pressure of the atmosphere in the habitat?

26-18. What industries use microjoining?

26-19. What is the advantage of Dabber welding?

26-20. What processes are used by the Dabber method?

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Appendix

OUTLINE

A-1 GLOSSARY OF WELDING TERMS

Air*: Slang for oxygen, should not use.

All-Weld-Metal-Test-Specimen*: A test specimen with the reduced section composed wholly of weld metal.

Alternating Current or AC*: Electricity that reverses its direction periodically. For cycle current, the current goes in one direction and then in the other direction 60 times in the same second, so that the current changes its direction 120 times in 1 second.

Ammeter*: An instrument for measuring either direct or alternating electric current (depending on its construction). Its scale is usually graduated in amperes and milliamperes.

Anode*: The positive terminal of an electrical source.

Arc Blow: The deflection of an electric arc from its normal path because of magnetic forces.

Arc Length*: The distance from the end of the electrode to the point where the arc makes contact with work surface.

Arc Spot Weld: A spot weld made by an arc welding process.

Arc Voltage: The voltage across the welding arc.

Arc Wander*: Wander or drifting of arc in various directions. (*See also* Arc Blow.)

*Asterisks indicate that the term is not the official AWS term.

As-Welded: The condition of weld metal, welded joints, and weldments after welding but prior to any subsequent thermal, mechanical, or chemical treatments.

Autogenous Weld: A fusion weld made without the addition of filler metal.

Backfire: The momentary recession of the flame into the welding tip or cutting tip followed by immediate reappearance or complete extinction of the flame.

Backing: A material or device placed against the back side of the joint, or at both sides of a weld in electroslag and electrogas welding, to support and retain molten weld metal. The material may be partially fused or remain unfused during welding and may be either metal or nonmetal.

Backstep Sequence: A longitudinal sequence in which weld passes are made in the direction opposite to the progress of welding.

Base Material: The material to be welded, brazed, soldered, or cut. (*See also* substrate.)

Bell Hole Welding*: A pipeline term whereby the pipe sections are welded together to the end of the transmission line in position.

Bevel: An angular type of edge preparation.

Blacksmith Welding: *See* the preferred term, Forge Welding.

Bottle*: *See* the preferred term, Cylinder.

Boxing: The continuation of a fillet weld around a corner of a member as an extension of the principal weld.

Braze: A weld produced by heating an assembly to suitable temperatures and by using a filler metal, having liquids above 450 °C (842 °F) and below the solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

Buckling*: Distortion of sheet metal due to the forces of expansion and contraction caused by the application of heat.

Burner: *See* the preferred term, Oxygen Cutter.

Butt Joint: A joint between two members aligned approximately in the same plane.

Butt Weld: An erroneous term for a weld in a butt joint. (*See also* Butt Joint.)

Button Weld*: *See* Arc Spot Weld.

Cap Pass*: A pipeline term that refers to the final or reinforcing pass of the weld joint.

Carbon Steel*: Carbon steel is a term applied to a broad range of material containing: carbon 1.7% max., maganese 1.65% max., silicon 0.60% max. Carbon steel is subdivided as follows:

Low-carbon steels	0.15% C max.
Mild-carbon steels	0.15–0.29% C.
Medium-carbon steels	0.30–0.59% C.
High-carbon steels	0.60–1.70% C.

Cast Iron*: A wide variety of iron base materials containing carbon 1.7 to 4.5%; silicon 0.5 to 3%; phosphorus 0.8% max.; sulfur 0.2% max.; molybdenum, nickel, chromium, and copper can be added to produce alloyed cast irons.

Chamfer: *See* the preferred term, Bevel.

Covered Electrode: A composite filler metal electrode consisting of a core of a bare electrode or metal cored electrode to which a covering sufficient to provide a slag layer on the weld metal has been applied. The covering may contain materials providing such functions as shielding from the atmosphere, deoxidation, and arc stabilization, and can serve as a source of metallic additions to the weld.

Crater: A depression at the termination of a weld bead.

Cup: *See* the preferred term, Nozzle.

Cylinder*: A portable container used for transportation and storage of a compressed gas.

Depth of Fusion: The distance that fusion extends into the base metal or previous pass from the surface melted during welding.

Direct Current or DC*: Electric current that flows in only one direction. It is measured by an ammeter.

Double Ending*: A pipeline term meaning welding two lengths of pipe together, usually roll welding in the flat position.

Downhand: *See* the preferred term, Flat Position.

Downhill Welding*: A pipe welding term indicating that the weld progresses from top of the pipe to the bottom of the pipe. The pipe is not rotated.

Electrode: Tungsten Electrode: A non-filler metal electrode used in arc welding or cutting, made principally of tungsten.

Elongation*: Extension produced between two gauge marks during a tensile test. Expressed as a percentage of the original gauge length.

FabCO Welding*: Trade name; *see* Flux-Cored Arc Welding.

Face of Weld: The exposed surface of a weld on the side from which welding was done.

Filler Bead*: A pipeline term referring to the passes laid over the hot pass but not the next to last or final pass.

Fillet Weld: A weld of approximately triangular cross section joining two surfaces approximately at right angles to each other in a lap joint, T-joint, or corner joint.

Firing Line Welder*: A pipeline—a welder in the hot pass crew.

Flat Position: The welding position used to weld from the upper side of the joint; the face of the weld is approximately horizontal.

Flux: Material used to prevent, dissolve, or facilitate removal of oxides and other undesirable surface substances.

Flux-Cored Arc Welding (FCAW): An arc welding process that produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is provided by a flux contained within the tubular electrode. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture. (*See also* Flux-Cored Electrode.)

Flux-Cored Electrode: A composite filler metal electrode consisting of a metal tube or other hollow configuration containing ingredients to provide such functions as shielding atmosphere, deoxidation, arc stabilization and slag formation. Alloying materials may be included in the core. External shielding may or may not be used.

Forge Welding: A solid-state welding process that produces coalescence of metals by heating them in air in a forge and by applying pressure or blows sufficient to cause permanent deformation at the interface.

Friction Welding: A solid-state welding process that produces coalescence of materials by the heat obtained from a mechanically induced sliding motion between rubbing surfaces. The work parts are held together under pressure.

Furnace Brazing (FB): A brazing process in which the workpieces are placed in a furnace and heated to the brazing temperature.

Gas Metal Arc Welding (GMAW): An arc welding process that produces coalescence of metals by heating them with an arc between a continuous filler metal electrode and the workpieces. Shielding is obtained entirely from an externally supplied gas or gas mixture. Some methods of this process are called MIG or CO_2 welding.

Gas Pocket*: Pipeline term for porosity.

Gas Shielded Metal Arc Welding: A general term used to describe gas metal arc welding, gas tungsten arc welding, and flux-cored arc welding when gas shielding is employed.

Gas Tungsten Arc Welding (GTAW): An arc welding process that produces coalescence of metals by heating them with an arc between a tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture. Pressure may or may not be used and filler metal may or may not be used. (This process has sometimes been called TIG welding.)

Groove Weld: A weld made in the groove between two members to be joined. The standard types of groove welds are as follows: double-bevel-groove weld, double-flare-bevel-groove weld, double-flare-V-groove weld, double-J-groove weld, double-U-groove weld, double-V-groove weld, single-bevel-groove weld, single-flare-bevel-groove weld, single-flare-V-groove weld, single-J-groove weld, single-U-groove weld, single-V-groove weld, and square-groove weld.

Ground Connection: An electrical connection of the welding machine frame to the earth for safety. (*See also* Workpiece Connection and Workpiece Lead.)

Ground Lead: *See* the preferred term, Workpiece Lead.

Heat-Affected Zone: That portion of the base metal that has not been melted, but whose mechanical properties or microstructure have been altered by the heat of welding, brazing, soldering, or cutting.

Heliarc*: Trade name; *see* Gas Tungsten Arc Welding.

Hollow Bead*: Pipeline term for porosity in the root reinforcement.

Horizontal Position: Fillet weld; the position in which welding is performed on the upper side of an approximately horizontal surface and against an approximately vertical surface. Groove weld; the position of welding in which the axis of the weld lies in an approximately horizontal plane and the face of the weld lies in an approximately vertical plane.

Hot Pass*: A pipeline term that refers to the second pass or the pass over the stringer bead. The hot pass is usually made at high currents to practically remelt the entire stringer bead.

Impact Resistance*: Energy absorbed during breakage by impact of specially prepared notched specimen, the result being commonly expressed in foot-pounds.

Induction Brazing: A brazing process in which the heat required is obtained from the resistance of the work to induced electric current.

Inertia Friction Welding: A variation of friction welding in which the energy required to make the weld is supplied primarily by the stored rotational kinetic energy of the welding machine.

Joint Penetration: The depth a weld extends from its face into a joint, exclusive of reinforcement.

Joint Welding Procedure:* The materials, detailed methods and practices employed in the welding of a particular joint.

Kerf: The width of the cut produced during a cutting process.

Land: A nonstandard term for root face.

Lap Joint: A joint between two overlapping members in parallel planes.

Lead Burning: An erroneous term used to denote the welding of lead.

Low-Alloy Steel*: Low-alloy steels are those containing low percentages of alloying elements.

Melting Rate: The weight or length of electrode melted in a unit of time.

Micro-Wire Welding*: Trade name; *see* Gas Metal Arc Welding.

MIG Welding*: *See* the preferred terms, Gas Metal Arc Welding and Flux-Cored Arc Welding.

Molten Weld Pool: *See* the preferred term, Weld Pool.

Nose*: *See* Root Face.

Nozzle: A device that directs shielding media.

Off-Center Coating*: When flux coating on a covered electrode is thicker on one side than the opposite side.

Open-Circuit Voltage: The voltage between the output terminals of the welding machine when no current is flowing in the welding circuit.

Overfill*: Excessive reinforcement.

Overhead Position: The position in which welding is performed from the underside of the joint.

Overlap: The protrusion of weld metal beyond the toe, face, or root of the weld.

Oxygen Cutter: One who performs a manual oxygen cutting operation.

Parent Metal: *See* the preferred terms, Base Metal and Substrate.

Pass: *See* Weld Pass.

Peening: The mechanical working of metals using impact blows.

Penetration: *See* the preferred terms, Joint Penetration and Root Penetration.

Performance Qualification*: Methods, tests, and acceptable standards used to qualify a welding procedure.

Porosity: Cavity-type discontinuities formed by gas entrapment during solidification.

Postheating: *See* Postweld Heat Treatment.

Postweld Heat Treatment: Any heat treatment after welding.

Preheating: The application of heat to the base metal immediately before welding, brazing, soldering, or cutting.

Procedure Qualification: The demonstration that welds made by a specific procedure can meet prescribed standards.

Procedure Specification*: A very complete and formal welding procedure written in accordance with code.

Psi*: Pounds per square inch.

Puddle: *See* the preferred term, Weld Pool.

Quarter Weld*: Pipe welding making the joint in four segments rotating the pipe 90° between each segment.

QWP*: Qualified welding procedure.

Radiography*: The use of radiant energy in the form of x-rays or gamma rays for the nondestructive examination of metals.

Reduction of Area*: The difference between he original cross-sectional area and that of the smallest area at the point of rupture; usually states as a percentage of the original area.

Returning (Boxing)*: The practice of continuing a weld around a corner as an extension of the principal weld.

Reverse Polarity: A nonstandard term for direct current electrode positive.

Rheostat*: A variable resistor which has one fixed terminal and a movable contact (often erroneously referred to as a "two-terminal potentiometer"). Potentiometers may be used as rheostats, but a rheostat cannot be used as a potentiometer, because connections cannot be made to both ends of the resistance element.

Root Face: That portion of the groove face adjacent to the root of the joint.

Root Gap: *See* the preferred term, Root Opening.

Root of Weld: *See* Weld Root.

Root Opening: The separation at the joint root between the workpieces.

Root Penetration: The depth that a weld extends into the root of a joint measured on the centerline of the root cross section.

Seal Weld: Any weld designed primarily to provide a specific degree of tightness against leakage.

Shielded Metal Arc Welding (SMAW): An arc welding process that produces coalescence of metals by heating them with an arc between a covered metal electrode and the workpiece. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode.

Shoulder: *See* the preferred term, Root Face.

Silver soldering: Nonpreferred term used to denote brazing with a silver-base filler metal. (*See also* the preferred terms, Furnace Brazing, Induction Brazing, and Torch Brazing.)

Size of Weld*: Groove weld—the joint penetration (depth of bevel plus the root penetration when specified). The size of a groove weld and its effective throat are one and the same. Fillet weld—for equal-leg fillet welds, the leg lengths of the largest isosceles right triangle which can be inscribed within the fillet weld cross section. For unequal-leg fillet welds, the leg lengths of the largest right triangle which can be inscribed within the fillet weld cross section. When one member makes an angle with the other member greater than 105°, the leg length (size) is of less significance than the effective throat which is the controlling factor for the strength of a weld.

Slag Inclusion: Nonmetallic solid material entrapped in weld metal or between weld metal and base metal.

Slugging: The act of adding a separate piece or pieces of material in a joint before or during welding that results in a welded joint, not complying with design, drawing, or specification requirements.

Spatter: The metal particles expelled during fusion welding and which do not form a part of the weld.

Squirt Welding*: Semiautomatic and submerged arc welding.

Stick Welding*: Welding using shielded metal arc welding.

Stinger*: Electrode holder.

Stove Pipe Welding*: A pipeline term whereby each length of pipe is joined to the transmission line in a progressive fashion with each joint made in position.

Straight Polarity: A nonstandard term for direct current electrode negative.

Stress Relief Heat Treatment: Uniform heating of a structure or a portion thereof to a sufficient temperature to relieve the major portion of the residual stresses, followed by uniform cooling.

Stringer Bead: A type of weld bead made without appreciable weaving motion. (*See also* Weave Bead.)

Stripper*: A pipeline term referring to the pass that brings the weld groove flush with the surface of the pipe.

Substrate: Any base material to which a thermal sprayed coating or surfacing weld is applied.

Tack Weld: A weld made to hold parts of a weldment in proper alignment until the final welds are made.

Tensile Strength*: The maximum load per unit of original cross-sectional area obtained before rupture of a tensile specimen. Measured in pounds per square inch.

Theoretical Throat: The distance from the beginning of the root of the joint perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the fillet weld cross section. Actual throat; the shortest distance from the root of a fillet weld to its face. Effective throat; the minimum distance minus any reinforcement from the root of a weld to its face.

TIG Welding*: *See* Gas Tungsten Arc Welding.

Toe of Weld: *See* Weld Toe.

Torch Brazing: A brazing process in which the heat required is furnished by a fuel gas flame.

Tungsten Electrode: *See* Electrode: Tungsten Electrode.

Ultimate Tensile Strength*: The maximum tensile stress which will cause a material to break (usually expressed in pounds per square inch).

Underbead Crack: A crack in the heat-affected zone generally not extending to the surface of the base metal.

Undercut: A groove melted into the base metal adjacent to the toe or root of a weld and left unfilled by weld metal.

Underfill: A depression on the face of the weld or root surface extending below the surface of the adjacent base metal.

Uphill Welding*: A pipe welding term indicating that the welds are made from the bottom of the pipe to the top of the pipe. The pipe is not rotated.

VAE*: Visually acceptable external—inspection of a weld.

Vertical Position: The position of welding in which the axis of the weld is approximately vertical.

Weave Bead: A type of weld bead made with transverse oscillation.

Weaving*: A technique of depositing weld metal in which the electrode is oscillated.

Weld: A localized coalescence of metals or nonmetals produced either by heating the materials to welding temperatures, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler material.

Weld Metal: That portion of a weld which has been melted during welding.

Weld Pool: The localized volume of molten metal in a weld prior to its solidification as weld metal.

Weld Puddle: A nonstandard term for weld pool.

Weld Root: The points, as shown in cross section, at which the back of the weld intersects the base metal surfaces.

Weld Toe: The junction of the weld face and the base metal.

Welder: One who performs a manual or semiautomatic welding operation. (Sometimes erroneously used to denote a welding machine.)

Welding Ground: *See* the preferred term, Workpiece Connection.

Welding Procedure: The detailed methods and practices including all joint welding procedures involved in the production of a weldment. (*See also* Joint Welding Procedure.)

Welding Procedure Specification (WPS): A document providing in detail the required variables for specific application to assure repeatability by properly trained welders and welding operators.

Welding Process: A joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal. See also the master chart of welding and allied processes.

Welding rod: A form of welding filler metal, normally packaged in straight lengths, that does not conduct electrical current.

Weldment: An assembly whose component parts are joined by welding.

Weldor: *See* the preferred term, Welder.

Whipping*: A term applied to an inward and upward movement of the electrode which is employed in vertical welding to avoid undercut.

Wire Welding*: *See* Gas Metal Arc Welding.

Workpiece Connection: The connection of the work lead to the work.

Workpiece Lead: The electric conductor between the source of arc welding current and the work.

A-2 ORGANIZATIONS INVOLVED WITH WELDING

AIA: Aerospace Industries Association of America, 1725 De Sales Street, N.W., Washington, DC 20036. A national industry association of companies in U.S. engaged in the research, development, and manufacture of aerospace systems, missiles and astronautical vehicles, their propulsion or control units or associated equipment.

AA: Aluminum Association, 750 Third Avenue, New York, NY 10017. An industry association of producers of aluminum. The association aim is to increase understanding of the aluminum industry, to provide technical, statistical, and marketing information.

AASHT: American Association of State Highway Transportation, Suite 341, National Press Building, Washington, DC 20045. An association of state transportation officials. The AASHT issues various standards and specifications.

ABS: American Bureau of Shipping, 45 Eisenhower Drive, Paramus, NJ 07652. A nonprofit classification society. Telephone (201)368-9100. Classification is a service for shipowners to establish that the ship has been built to recognized standards. ABS provides rules for building ships and issues approvals for welding filler metals.

AFS: American Foundrymen's Society, Golf and Wolf Roads, Des Plains, IL 60016. A technical society devoted to the advancement of manufacture and utilization of castings through research, education, and dissemination of technology.

AISC: American Institute of Steel Construction, 1221 Avenue of the Americas, New York, NY 10020. An industry association of fabricated structural steel producers. AISC provides design information and standards pertaining to structural steel.

AISI: American Iron and Steel Institute, 1000 Sixteenth Street, N.W., Washington, DC 20036. An industry association of the iron and steel producers. It provides statistics on steel production and use and publishes the steel products manuals.

ANSI: American National Standards Institute, 1430 Broadway, New York, NY 10018. ANSI formerly the United States of America Standards Institute (USASI) formerly the American Standard Association (ASA). ANSI is the U.S. representative to ISO. It is a nonprofit corporation that publishes National Standards in cooperation with technical and engineering societies, trade associations, and government agencies.

API: American Petroleum Institute, 1801 K Street, Washington, DC 20006. An association of the petroleum industry. It publishes various standards involved with welding including cross-country pipeline welding, storage tanks, and line pipe.

AREA: American Railway Engineering Association, 59 East Van Buren Street, Chicago, IL 60605. An engineering society which, through committes, develops standards applicable to railroads. Several of these involve welding.

ASME: American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017. An engineering society which, among other things, publishes the boiler and pressure vessel code. Section IX is the welding qualification section of this code. Telephone (212) 705-7740.

ASM: American Society for Metals, Metals Park, OH 44073. A technical society that seeks to advance the knowledge of metals and materials, their engineering, design, processing and fabricating, through research education and dissemination of information.

ASNT: American Society for Nondestructive Testing, 4153 Arlingate Plaza, Caller #28519, Columbus, OH 43228. The pur-

pose of this engineering society is scientific and educational, directed toward the advancement of theory and practice of nondestructive test methods for improved product quality and reliability. Telephone (614) 274-6003.

ASQC: American Society for Quality Control, Inc., 161 West Wisconsin Avenue, Milwaukee, WI 53203. An engineering society that seeks to create, promote, and stimulate interest in the advancement and diffusion of knowledge of the science of control and its application to the quality of industrial products.

ASTM: American Society of Testing and Materials, 1916 Race Street, Philadelphia, PA, 19103. A scientific and technical organization for standards, materials, products, systems. It is the world's larges source of voluntary consensus standards.

AWWA: American Water Works Association, 6666 West Quincy Avenue, Denver, CO 80235. An industry association of water companies and companies serving the water supply industry. It publishes numerous standards, several in cooperation with AWS.

AWI: American Welding Institute, New Topside Road, Route 4, Box 90, Louisville, TN 37777. A nonprofit development and technology transference organization devoted to welding. Telephone (615) 970-2150.

AWS: American Welding Society, 550 N.W. LeJeune Road, P.O. Box 351040, Miami, FL 33135. Telephone (305) 443-9353. A nonprofit technical society organized and founded for the purpose of advancing the art and science of welding. The AWS publishes codes and standards concerning all phases of welding and *The Welding Journal.*

AAR: Association of American Railroads, 1920 L Street, N.W., Washington, DC 20036. An industry association of railroads. Among other things, it publishes specifications for rolling stock, welding qualifications and so on.

AWI: Australian Welding Institute, Eagle House, 118 Alfred Street, Milsons Point, N.S.W., Australia 2061. The national welding society of Australia.

BSI: British Standards Institution, 2 Park Street, London, England. A nonprofit concern. The principal object is to coordinate the efforts of producers and users for the improvement, standardization, and simplification of engineering and industrial material.

CSA: Canadian Standards Association, 178 Rexdale Boulevard, Rexdale, Ontario, Canada M9W 1R3. A National Association of Technical Committees to provide a national standardizing body for Canada. It publishes many standards involving welding.

CWB: Canadian Welding Bureau, 254 Merton Street, Toronto, Ontario, Canada M4S 1A9. A division of the CSA, its purpose is to provide the necessary codes and standards covering all phases of welding, for the guidance of fabricators, designers, architects, consulting engineers, and governmental departments.

CGA: Compressed Gas Association, 500 Fifth Avenue, New York, NY 10036. A nonprofit membership association and technical organization interested in both adequate data and sound utilization for gases.

CDA: Copper Development Association, 57th Floor, Chrysler Building, 405 Lexington Avenue, New York, NY 10017. A trade association of copper producers. Publishes standards of commercial copper mill products and standard designations for copper and copper alloys.

DVS: Deutscher Verband fur Schweisstechnik e.V., Aachener Strasse 172, Postfach 27 25, D-4000 Dusseldorf 1, FRG. The national welding society of West Germany.

EWI: Edison Welding Institute, 1100 Kinnear Road, Columbus OH 43212. A nonprofit applied engineering center dedicated to welding and related joining technologies. Telephone (614) 486-4400.

IIW: International Institute of Welding. Contact your local welding society. An international society of national associations to promote the development of welding and assist in the international standards for welding in collaboration with the ISO.

ISO: International Organization for Standardization, Paris, France, is a worldwide federation of national standards institutes.

JIS: Japanese Industrial Standards, I-24 Akasaka, 4-chome, Minato-ku, Tokyo 107, Japan. The Japanese Standards Association publishes standards including metals, welding filler metals, and so on.

Lloyd's Register of Shipping Trust Corp. Inc., 71 Fenchurch Street, London EC3M 4BS, England. This society was established for the purpose of obtaining for the use of merchants, shipowners, and underwriters a faithful and accurate classification of mercantile shipping. The society approves design, surveys, apparatus, material, and so on.

MCAA: Mechanical Contractors Association of America, 5530 Wisconsin Avenue N.W., Washington, DC 20015. Formerly Heating, Piping and Air-Conditioning Contractors National Association. A trade association of contractors in the piping, heating and air-conditioning business. It sponsors the National Certified Pipe Welding Bureau.

NBBPVI: National Board of Boiler and Pressure Vessel Inspectors, 1055 Crupper Drive, Columbus, OH 43229. An organization of chief boiler inspectors of the states and cities in the U.S. and provinces of Canada. The national board enforces the various sections of the ASME boiler code.

NCPWB: National Certified Pipe Welding Bureau, 5530 Wisconsin Avenue, Suite 750, Washington, DC 20015. A division of the Mechanical Contractors Association of America, Inc. Its purpose is to develop and test procedures and, through its local chapters, to establish pools of workers qualified to weld under these procedures.

NEMA: National Electrical Manufacturers Association, 2101 L. Street N.W. Washington, DC 20037. An industry association of manufacturers of electrical machinery. Publishes standards and industry statistics including welding.

NFPA: National Fire Protection Association, 470 Atlantic Avenue, Boston, MA 02210. An organization dedicated to promote the science and improve the methods of fire protection. NFPA publishes the *National Electrical Code®* . The code provides safety installation information for welding machines.

NWSA: National Welding Supply Association, 1900 Arch Street, Philadelphia, PA 19103. And industry association of welding supply distributors. Telephone (215) 564-3484.

PFI: Pipe Fabrication Institute, 1326 Freeport Road, Pitts-

burgh, PA 15238. An association of the pipe-fabricating industry.

PLCA: Pipe Line Contractors Association, 2800 Republic National Bank Building, Dallas, TX 75201. An industry association of contractors that build underground pipelines, especially cross-country pipelines.

RWMA: Resistance Welder Manufacturer Association, 1900 Arch Street, Philadelphia, PA 19103. An association of manufacturers of resistance welding equipment. Establishes standards for welding equipment and procedure information.

SAE: Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15086. An engineering society with the objective to promote the arts, sciences, standards, and engineering practices connected with the design, construction and utilization of self-propelled mechanisms, prime movers, components thereof, and related equipment.

SFSA: Steel Founders' Society of America, 20611 Center Ridge Road, Rocky River, OH 44116. The Steel Founders' Society is an association of companies engaged in the manufacture of steel castings. They publish technical bulletins, the *Steel Castings Handbook* and the *Journal of Steel Castings Research*.

SPFA: Steel Plate Fabricators association, 15 Spinning Wheel Road, Hinsdale, IL 60521. A nonprofit industry association of metal plate fabricators.

TWI: The Welding Institute, Abington Hall, Cambridge, England. A professional institute to further the exchange of technical knowledge by meetings, publications, a library and information service, and courses in its School of Welding Technology. Its research division provides research on welding.

UL: Underwriters' Laboratories, Inc., 207 East Ohio Street, Chicago, IL 60611. The Underwriters' Laboratories, Inc., is a nonprofit organization that operates laboratories for the examination and testing of devices, systems and materials. They publish standards for safety for oxyfuel gas torches, regulators, gauges, acetylene generators, transformer type arc welding machines, and for many other items.

WIC: Welding Institute of Canada/Institut de Soudage du Canada, 391 Burnhamthorpe Rd. East, Oakville, Ontario L6J 6C9. The National Welding Society of Canada, combined with the National Welding Research and Development Institute. Telephone (416) 845-9881.

WRC: Welding Research Council, 345 E. 47th Street, New York, NY 10017. A nonprofit association organized to provide a mechanism for conducting cooperative research work in the welding field. (212) 705-7080.

A-3 COMPUTER SOFTWARE PROGRAMS

Recent advances in computer capabilities and widespread use of personal computers has greatly affected the welding industry. Software programs are now available to help organize and provide information on a variety of welding subjects. The following software programs will be of interest to readers. Please consult the software publisher for more details. See Appendix A-2 for addresses.

Available from the American Welding Institute:

- Weldselector. Assists in selecting the optimum welding electrode for any particular job based on asking a series of questions.

  Weldertrack. Assists foremen and managers by providing information about welders and projects under their supervision. It can tabulate reject rates, welder tasks, welding method and other factors.
- Additional programs are being developed. Demonstration disks are available to explain the programs more completely.

Available from the Edison Welding Institute and The Welding Institute:

- Weldvol. Allows the engineer or cost analyst to make fast and accurate calculations of weld volumes and consumables required for cost estimating and consumable orderings of welding jobs.
- Weldcost. Allows the engineer to analyze welding costs per foot of welded fabrications. Weldcost and Weldvol used together provide easy and fast costing of welding jobs.
- Weldspec. Allows easy storage and fast retrieval of procedure qualification records. Welding procedures are also filed, avoiding costly requalification if a suitable similar procedure exists.
- Preheat. This program quickly guides the welding engineer through a determination exercise to establish the correct preheat when welding carbon and carbon manganese steels.
- Welderqual. This program automates the storage and retrieval of welder qualification records. It can be used for different codes. The program warns of qualifications which are about to expire. It also allows identification of welders qualified for specific procedures.
- Additional programs are being developed. Demonstration disks are available to explain the program more completely.

Available from Hobart:

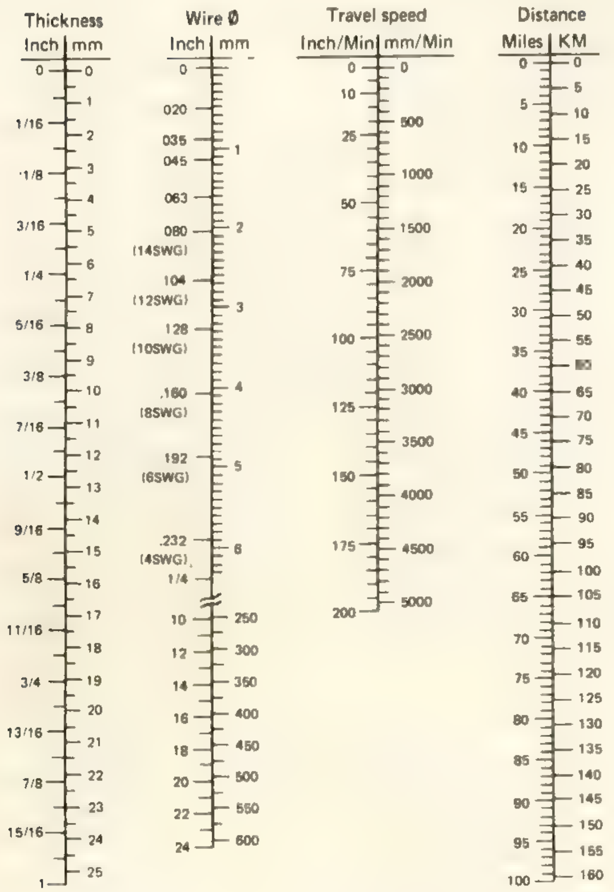
- Weldassist. This is a diagnostic program to help welders and supervisors diagnose the cause of faulty welds. It is helpful for robot welding applications using GMAW on carbon steels
- Programs are also available for NDT and for automatic thermal cutting.

More and more welding related programs are becoming available. Consult the welding and metal working periodicals for new offerings.

A-4 CONVERSION INFORMATION

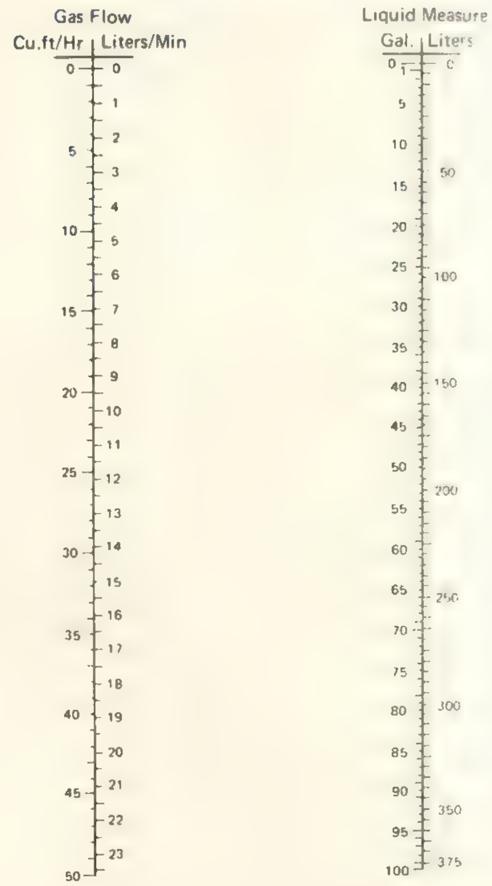
Length, or Distance and Speed Conversion

Approximate Conversion



Flow Rate–Liquid Measure

Approximate Conversion



Exact Conversion

For use with electronic calculators—First enter the conversion constant number. Press the x button. Enter the known quantity of the dimension. Press the =. The desired value of the dimension will appear on the display.

25.40	×	___ inch	=	___ mm
304.8	×	___ feet	=	___ mm
.0393	×	___ mm	=	___ inch
.00328	×	___ mm	=	___ feet
.0621	×	___ km	=	___ miles
1.609	×	___ miles	=	___ Kilometers
.4233	×	___ in/min	=	___ mm/second
2.362	×	___ mm/s	=	___ in/min.

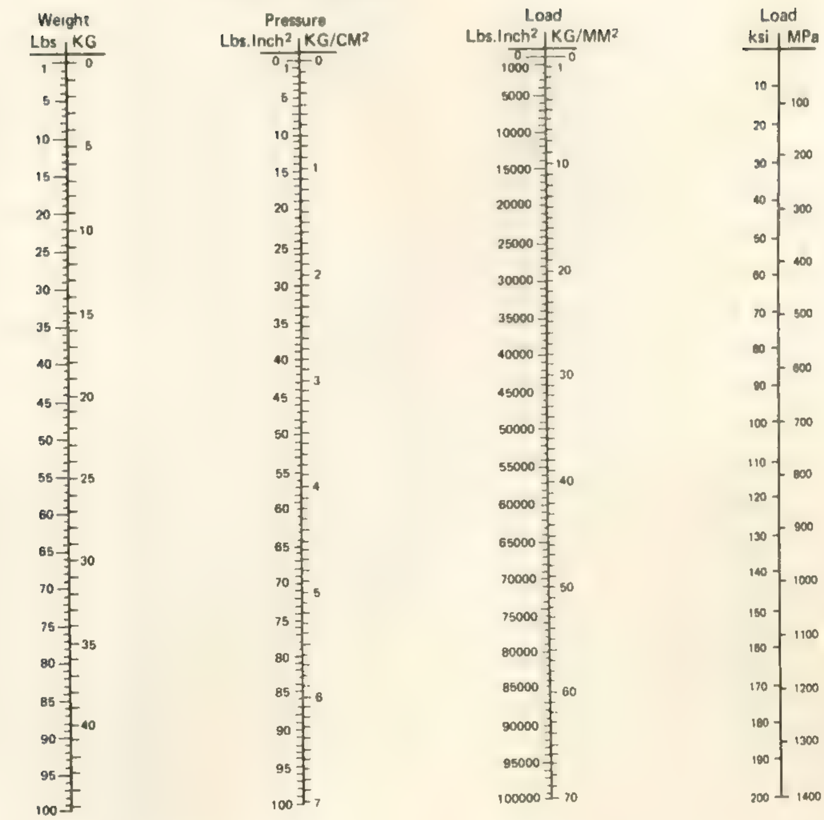
Exact Conversion

For use with electronic calculators. First enter the conversion constant number. Press the × button. Enter the known quantity of the dimension. Press the =. The desired value of the dimension will appear on the display.

0.4719	×	___ cu ft/hr	=	___ litre/min.
2.119	×	___ L/min	=	___ cu ft/hr.
3.785	×	___ gal/min	=	___ litre/min.
0.264	×	___ Litre/min	=	___ gal/min.
645.2	×	___ in^2	=	___ mm^2
0.00155	×	___ mm^2	=	___ in^2

Weight—Pressure—Load

Approximate Conversion



Exact Conversion

For use with electronic calculators—First enter the conversion constant number. Press the [×] button. Enter the known quantity of the dimension. Press the [=]. The desired value of the dimension will appear on the display

.000703	[×]	___	lb/in^2	[=]	___	kg/mm^2
6,894.7	[×]	___	lb/in^2	[=]	___	Kilo Pascal (KPa)
0.006895	[×]	___	lb/in^2	[=]	___	Mega Pascal (MPa)
0.07030	[×]	___	lb/in^2	[=]	___	kg/cm^2
14.2234	[×]	___	kg/cm^2	[=]	___	lbs/in^2
1422.34	[×]	___	kg/mm^2	[=]	___	lb/in^2 (PSI)
	[×]	___	kg/mm^2	[=]	___	Pascal (Pa)
	[×]	___	kg/mm^2	[=]	___	Kilo Pascal (KPa)
0.00145	[×]	___	Pa	[=]	___	lb/in^2 (PSI)
0.145	[×]	___	KPa	[=]	___	lb/in^2 (PSI)
	[×]	___	Pa	[=]	___	kg/mm^2
	[×]	___	KPa	[=]	___	kg/mm^2
4.448	[×]	___	lbs	[=]	___	Newton (N)
9.807	[×]	___	kg	[=]	___	Newton (N)
.2248	[×]	___	N	[=]	___	lbs
.1009	[×]	___	N	[=]	___	kg
0.4536	[×]	___	lbs	[=]	___	kg
2.205	[×]	___	kg	[=]	___	lbs

Metric Prefixes

Exponential Expression	Multiplication Factor	Prefix	Symbol
10^{12}	1 000 000 000 000	tera	T
10^{9}	1 000 000 000	giga	G
10^{6}	1 000 000	mega	M
10^{3}	1 000	kilo	k
10^{2}	100	hecto*	h
10	10	deka*	da
10^{-1}	0.1	deci*	d
10^{-2}	0.01	centi*	c
10^{-3}	0.001	milli	m
10^{-6}	0.000 001	micro	μ
10^{-9}	0.000 000 001	nano	n
10^{-12}	0.000 000 000 001	pico	p
10^{-15}	0.000 000 000 000 001	femto	f
10^{-18}	0.000 000 000 000 000 001	atto	a

*Rarely Used

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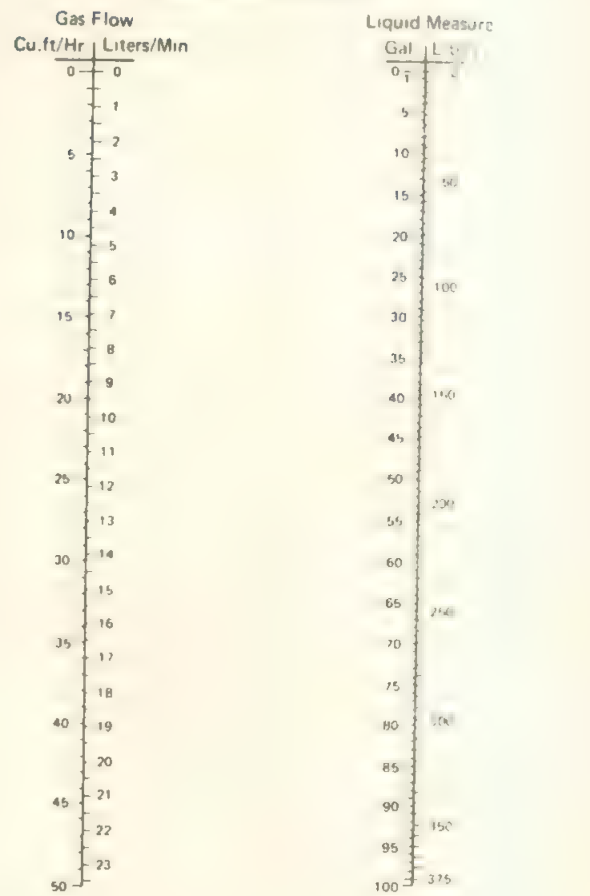
Length, or Distance and Speed Conversion

Approximate Conversion

Flow Rate—Liquid Measure

Approximate Conversion



Exact Conversion

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25.40	[x]	___ inch	[=]	___ mm
304.8	[x]	___ feet	[=]	___ mm
.0393	[x]	___ mm	[=]	___ inch
.00328	[x]	___ mm	[=]	___ feet
.0621	[x]	___ km	[=]	___ miles
1.609	[x]	___ miles	[=]	___ Kilometers
.4233	[x]	___ in/min	[=]	___ mm/second
2.362	[x]	___ mm/s	[=]	___ in/min.

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0.4719	[x]	___ cu ft/hr	[=]	___ litre/min.
2.119	[x]	___ L/min	[=]	___ cu ft/hr.
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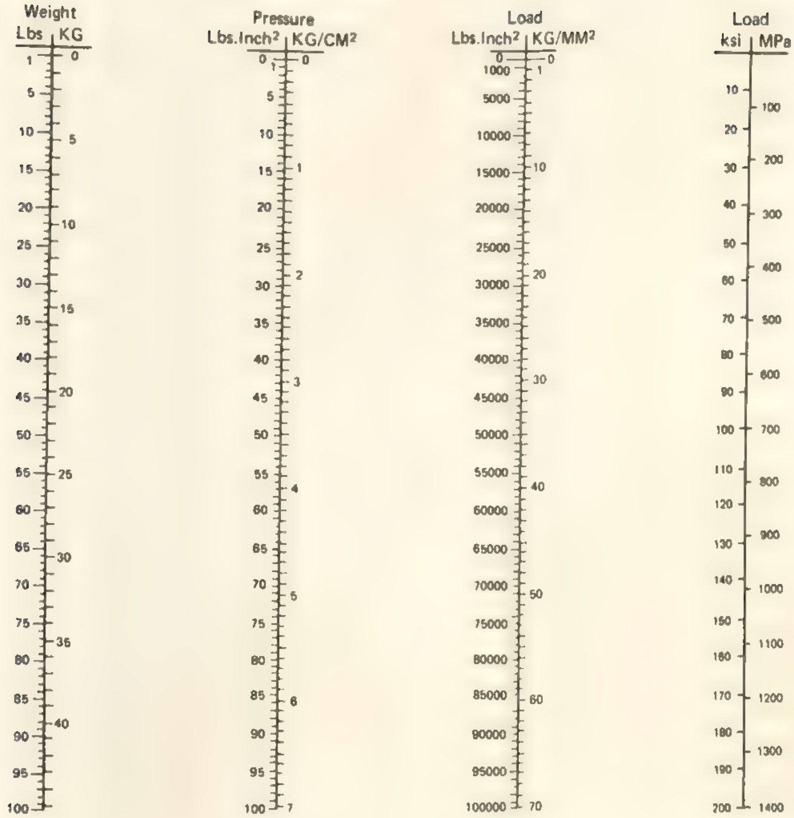
0.264	[x]	___ Litre/min	[=]	___ gal/min.
645.2	[x]	___ in^2	[=]	___ mm^2
0.00155	[x]	___ mm^2	[=]	___ in^2

Weight—Pressure—Load

Approximate Conversion



Exact Conversion

For use with electronic calculators. First enter the conversion constant number. Press the ☒ button. Enter the known quantity of the dimension. Press the ⊟. The desired value of the dimension will appear on the display

.000703	☒	____ lb/in^2	⊟	____	kg/mm^2
6,894 7	☒	____ lb/in^2	⊟	____	Kilo Pascal (KPa)
0.006895	☒	____ lb/in^2	⊟	____	Mega Pascal (MPa)
0.07030	☒	____ lb/in^2	⊟	____	kg/cm^2
14.2234	☒	____ kg/cm^2	⊟	____	lbs/in^2
1422.34	☒	____ kg/mm^2	⊟	____	lb/in^2 (PSI)
	☒	____ kg/mm^2	⊟	____	Pascal (Pa)
	☒	____ kg/mm^2	⊟	____	Kilo Pascal (KPa)
0.00145	☒	____ Pa	⊟	____	lb/in^2 (PSI)
0.145	☒	____ KPa	⊟	____	lb/in^2 (PSI)
	☒	____ Pa	⊟	____	kg/mm^2
	☒	____ KPa	⊟	____	kg/mm^2
4.448	☒	____ lbs	⊟	____	Newton (N)
9.807	☒	____ kg	⊟	____	Newton (N)
.2248	☒	____ N	⊟	____	lbs
.1009	☒	____ N	⊟	____	kg
0.4536	☒	____ lbs	⊟	____	kg
2.205	☒	____ kg	⊟	____	lbs

Metric Prefixes

Exponential Expression	Multiplication Factor	Prefix	Symbol
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10^{9}	1 000 000 000	giga	G
10^{6}	1 000 000	mega	M
10^{3}	1 000	kilo	k
10^{2}	100	hecto*	h
10	10	deka*	da
10^{-1}	0.1	deci*	d
10^{-2}	0.01	centi*	c
10^{-3}	0.001	milli	m
10^{-6}	0.000 001	micro	μ
10^{-9}	0.000 000 001	nano	n
10^{-12}	0.000 000 000 001	pico	p
10^{-15}	0.000 000 000 000 001	femto	f
10^{-18}	0.000 000 000 000 000 001	atto	a

*Rarely Used

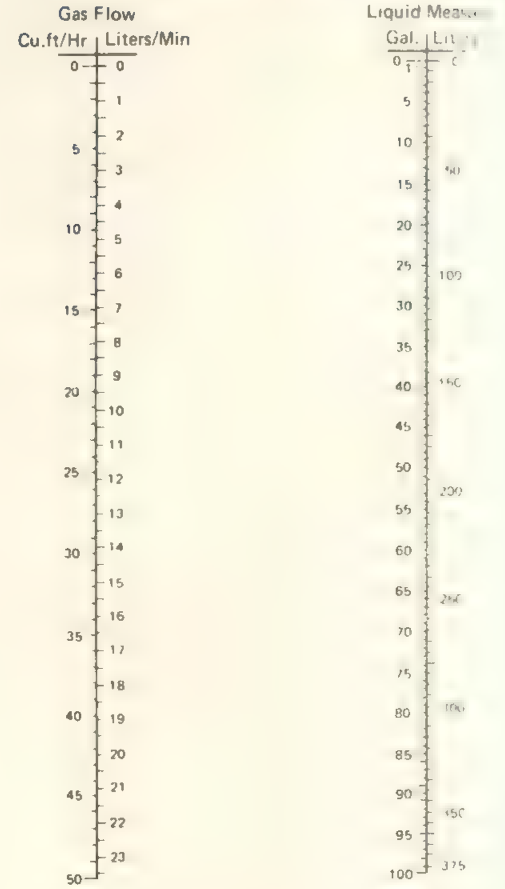
A-4 CONVERSION INFORMATION

Length, or Distance and Speed Conversion

Approximate Conversion

Flow Rate–Liquid Measure

Approximate Conversion



Exact Conversion

For use with electronic calculators–First enter the conversion constant number. Press the x button. Enter the known quantity of the dimension. Press the =. The desired value of the dimension will appear on the display.

25.40	x	__ inch	=	__ mm
304.8	x	__ feet	=	__ mm
.0393	x	__ mm	=	__ inch
.00328	x	__ mm	=	__ feet
.0621	x	__ km	=	__ miles
1.609	x	__ miles	=	__ Kilometers
.4233	x	__ in/min	=	__ mm/second
2.362	x	__ mm/s	=	__ in/min.

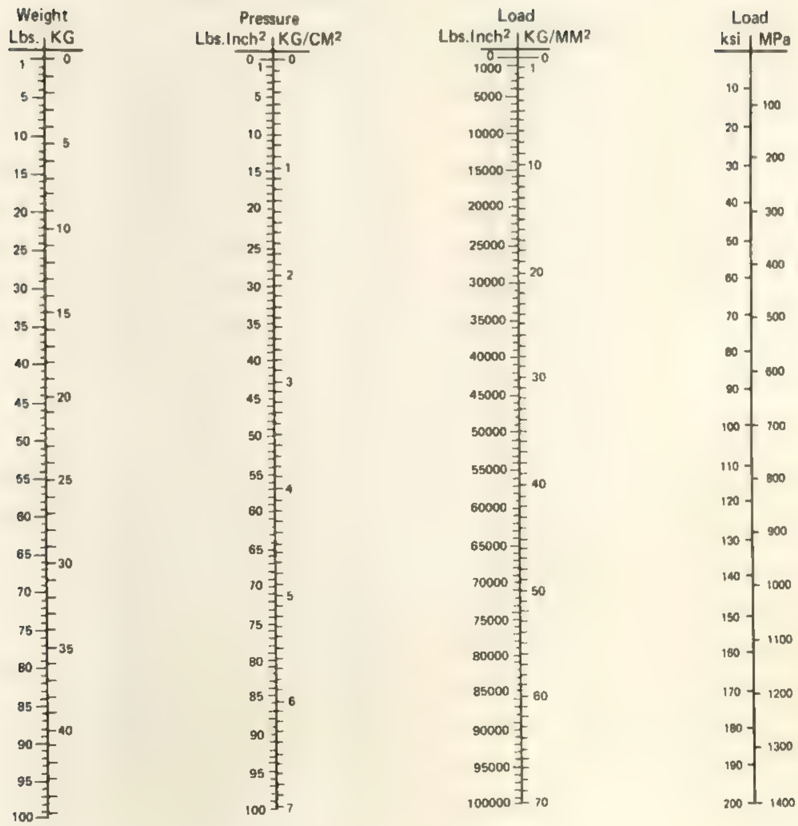
Exact Conversion

For use with electronic calculators. First enter the conversion constant number. Press the x button. Enter the known quantity of the dimension. Press the =. The desired value of the dimension will appear on the display.

0.4719	x	__ cu ft/hr	=	__ litre/min.
2.119	x	__ L/min	=	__ cu ft/hr.
3.785	x	__ gal/min	=	__ litre/min.
0.264	x	__ Litre/min	=	__ gal/min.
645.2	x	__ in^2	=	__ mm^2
0.00155	x	__ mm^2	=	__ in^2

Weight–Pressure–Load

Approximate Conversion



Exact Conversion

For use with electronic calculators – First enter the conversion constant number. Press the ☒ button. Enter the known quantity of the dimension. Press the ⊟. The desired value of the dimension will appear on the display

.000703	×	____	lb/in²	= ___	kg/mm²
6,894.7	×	____	lb/in²	= ___	Kilo Pascal (KPa)
0.006895	×	____	lb/in²	= ___	Mega Pascal (MPa)
0.07030	×	____	lb/in²	= ___	kg/cm²
14.2234	×	____	kg/cm²	= ___	lbs/in²
1422.34	×	____	kg/mm²	= ___	lb/in² (PSI)
	×	____	kg/mm²	= ___	Pascal (Pa)
	×	____	kg/mm²	= ___	Kilo Pascal (KPa)
0.00145	×	____	Pa	= ___	lb/in² (PSI)
0.145	×	____	KPa	= ___	lb/in² (PSI)
	×	____	Pa	= ___	kg/mm²
	×	____	KPa	= ___	kg/mm²
4 448	×	____	lbs	= ___	Newton (N)
9.807	×	____	kg	= ___	Newton (N)
.2248	×	____	N	= ___	lbs
.1009	×	____	N	= ___	kg
0.4536	×	____	lbs	= ___	kg
2.205	×	____	kg	= ___	lbs

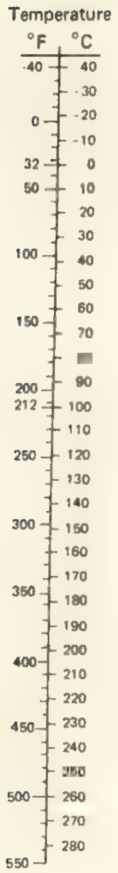
Metric Prefixes

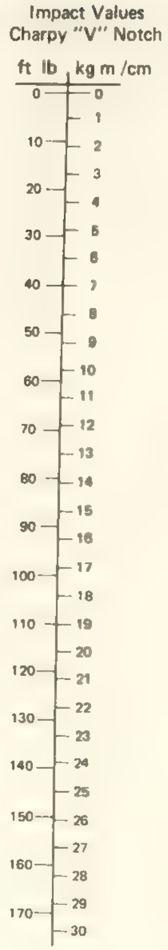
Exponential Expression	Multiplication Factor	Prefix	Symbol
10^{12}	1 000 000 000 000	tera	T
10^{9}	1 000 000 000	giga	G
10^{6}	1 000 000	mega	M
10^{3}	1 000	kilo	k
10^{2}	100	hecto*	h
10	10	deka*	da
10^{-1}	0.1	deci*	d
10^{-2}	0.01	centi*	c
10^{-3}	0.001	milli	m
10^{-6}	0.000 001	micro	μ
10^{-9}	0.000 000 001	nano	n
10^{-12}	0.000 000 000 001	pico	p
10^{-15}	0.000 000 000 000 001	femto	f
10^{-18}	0.000 000 000 000 000 001	atto	a

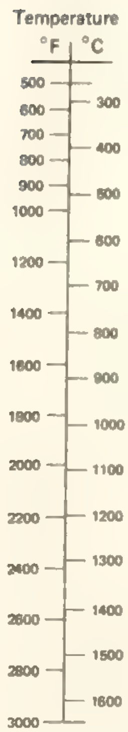
*Rarely Used

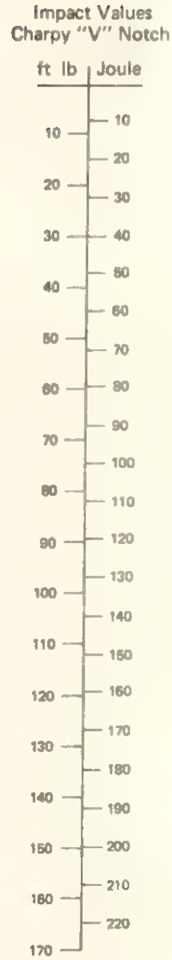
Temperature—Impact Values

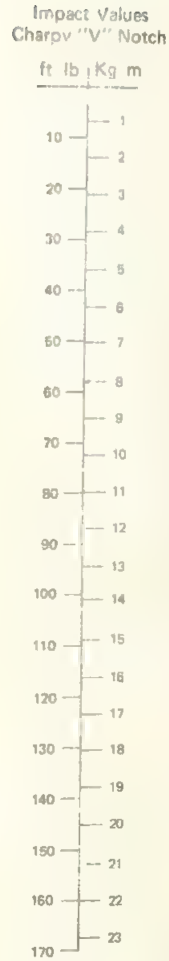
Approximate Conversion











Exact Conversion

For use with electronic calculators—First enter the conversion constant number. Press the $\boxed{\times}$ button. Enter the known quantity of the dimension. Press the $\boxed{=}$. The desired value of the dimension will appear on the display.

___°F $\boxed{-}$ 32 $\boxed{=}$ $\boxed{\times}$ .555 $\boxed{=}$ ___°C
___°C $\boxed{\times}$ 1.8 $\boxed{=}$ $\boxed{+}$ 32 $\boxed{=}$ ___°F

0.1383 $\boxed{\times}$ ___ ft-lbs $\boxed{=}$ ___ kg-m
7.233 $\boxed{\times}$ ___ kg-m $\boxed{=}$ ___ ft-lbs

1.356 $\boxed{\times}$ ___ ft-lbs $\boxed{=}$ ___ Joule
.7376 $\boxed{\times}$ ___ Joule $\boxed{=}$ ___ ft-lbs

.8 $\boxed{\times}$ ___ kg-m $\boxed{=}$ ___ kg-m/cm
0.1728 $\boxed{\times}$ ___ ft.lbs $\boxed{=}$ ___ kg-m/cm^2
5.787 $\boxed{\times}$ ___ kg-m/cm^2 $\boxed{=}$ ___ ft-lbs

A-5 WEIGHTS AND MEASURES

Impact values: sometimes metric values are kg-M/cm^2 if so multiply by 0.8 (area under notch).

Foot-Pounds	Kilogram-Meters	Joules	Foot-Pounds	Kilogram-Meters	Joules	Foot-Pounds	Kilogram-Meters	Joules
1	0.14	1.36	35	4.84	47.46	69	9.54	93.56
2	0.28	2.71	36	4.98	48.82	70	9.68	94.92
3	0.42	4.07	37	5.12	50.17	71	9.82	96.28
4	0.55	5.42	38	5.25	51.53	72	9.95	97.63
5	0.69	6.78	39	5.39	52.88	73	10.09	98.99
6	0.83	8.14	40	5.53	54.24	74	10.23	100.34
7	0.97	9.49	41	5.67	55.60	75	10.37	101.70
8	1.11	10.85	42	5.81	56.95	76	10.51	103.06
9	1.24	12.20	43	5.95	58.31	77	10.65	104.41
10	1.38	13.56	44	6.08	59.66	78	10.78	105.77
11	1.52	14.92	45	6.22	61.02	79	10.92	107.12
12	1.66	16.27	46	6.36	62.38	80	11.06	108.48
13	1.80	17.63	47	6.50	63.73	81	11.20	109.84
14	1.94	18.98	48	6.64	65.09	82	11.34	111.19
15	2.07	20.34	49	6.78	66.44	83	11.48	112.55
16	2.21	21.70	50	6.91	67.80	84	11.61	113.90
17	2.35	23.05	51	7.05	69.16	85	11.75	115.26
18	2.49	24.41	52	7.19	70.51	86	11.89	116.62
19	2.63	25.76	53	7.33	71.87	87	12.03	117.97
20	2.77	27.12	54	7.47	73.22	88	12.17	119.33
21	2.90	28.48	55	7.60	74.58	89	12.31	120.68
22	3.04	29.83	56	7.74	75.94	90	12.44	122.04
23	3.18	31.19	57	7.88	77.29	91	12.58	123.40
24	3.32	32.54	58	8.02	78.65	92	12.72	124.75
25	3.46	33.90	59	8.16	80.00	93	12.86	126.11
26	3.60	35.26	60	8.30	81.36	94	13.00	127.46
27	3.73	36.61	61	8.43	82.72	95	13.13	128.82
28	3.87	37.97	62	8.57	84.07	96	13.27	130.18
29	4.01	39.32	63	8.71	85.43	97	13.41	131.53
30	4.15	40.68	64	8.85	86.78	98	13.55	132.89
31	4.29	42.04	65	8.99	88.14	99	13.69	134.24
32	4.42	43.39	66	9.13	89.50	100	13.83	135.60
33	4.56	44.75	67	9.26	90.85			
34	4.70	46.10	68	9.40	92.21			

WIRE GAGES DIAMETER

U.S. Steel Wire Gage No.	in.	mm	U.S. Steel Wire Gage No.	in.	mm	U.S. Steel Wire Gage No.	in.	mm
7/0's	0.4900	12,447	11	0.1205	3.0607	28	0.0162	0.4115
6/0's	0.4615	11.7221	12	0.1055	2.6797	29	0.0150	0.381
5/0's	0.4305	10,9347	13	0.0915	2.3241	30	0.0140	0.3556
4/0's	0.3938	10.0025	14	0.0800	2.032	31	0.0132	0.3353
3/0's	0.3625	9.2075	15	0.0720	1.8389	32	0.0128	0.3251
2/0's	0.3310	8.4074	16	0.0625	1.5875	33	0.0118	0.2997
0	0.3065	7.7851	17	0.0540	1.3716	34	0.0104	0.2642
I	0.2830	7.1882	18	0.0475	1.2065	35	0.0095	0.2413
2	0.2625	6.6675	19	0.0410	1.0414	36	0.0090	0.2286
3	0.2437	6.1899	20	0.0348	0.8839	37	0.0085	0.2159
4	0.2253	5.7226	21	0.0317	0.8052	38	0.0080	0.2032
5	0.2070	5.2578	22	0.0286	0.7264	39	0.0075	0.1905
6	0.1920	4.8768	23	0.0258	0.6553	40	0.0070	0.1778
7	0.1770	4.4958	24	0.0230	0.5842	41	0.0066	0.1678
8	0.1620	4.1148	25	0.0204	0.5182	42	0.0062	0.1575
9	0.1483	3.7668	26	0.0181	0.4597	43	0.0060	0.1524
10	0.1350	3.429	27	0.0173	0.4394	44	0.0058	0.1473

Metric Conversion.

Inch. Fraction	Inch. Decimal	Millimeter	Inch. Fraction	Inch. Decimal	Millimeter	Inch. Fraction	Inc. Decimal	Millimeter
1/64	0.0158	0.3969	11/32	0.3437	8.7312	43/64	0.6719	17.0656
1/32	0.0312	0.7937	23/64	0.3594	9.1281	11/16	0.6875	17.4625
3/64	0.0469	1.1906	3/8	0.375	9.525	45/64	0.7031	17.8594
1/16	0.0625	1.5875	25/64	0.3906	9.9219	23/32	0.7187	18.2562
5/64	0.0781	1.9844	13/32	0.4062	10.3187	47/64	0.7344	18.6532
3/32	0.0937	2.3812	27/64	0.4219	10.7156	3/4	0.750	19.050
7/64	0.1094	2.7781	7/16	0.4375	11.1125	49/64	0.7656	19.4469
1/8	0.125	3.175	29/64	0.4531	11.5094	25/32	0.7812	19.8433
9/64	0.1406	3.5719	15/32	0.4687	11.9062	51/64	0.7969	20.2402
5/32	0.1562	3.9687	31/64	0.4844	12.3031	13/16	0.8125	20.6375
11/64	0.1719	4.3656	1/2	0.500	12.700	53/64	0.8281	21.0344
3/16	0.1875	4.7625	33/64	0.5156	13.0968	27/32	0.8437	21.4312
13/64	0.2031	5.1594	17/32	0.5312	13.4937	55/64	0.8594	21.8281
7/32	0.2187	5.5562	35/64	0.5469	13.8906	7/8	0.875	22.2250
15/64	0.2344	5.9531	9/16	0.5625	14.2875	57/64	0.8906	22.6219
1/4	0.25	6.35	37/64	0.5781	14.6844	29/32	0.9062	23.0187
17/64	0.2656	6.7469	19/32	0.5937	15.0812	59/64	0.9219	23.4156
9/32	0.2812	7.1437	39/64	0.6094	15.4781	15/16	0.9375	23.8125
19/64	0.2969	7.5406	5/8	0.625	15.875	61/64	0.9531	24.2094
5/16	0.3125	7.9375	41/64	0.6406	16.2719	31/32	0.9687	24.6062
21/4	0.3281	8.3344	21/32	0.6562	16.6687	63/64	0.9844	25.0031

Geometric Formula.

Areas

Paralleologram = base × altitude.
Triangle = half base × altitude.
Trapezoid = half the sum of the two parallel sides × the perpendicular distance between them.
Regular polygon = half of perimeter × the perpendicular distance from the center to any one side.
Circle = square of the diameter × 0.7854.
Sector of circle = number of degrees in arc × square of radius × 0.008727.
Segment of circle = area of sector with same arc minus area of triangle formed by radii of the arc and chord of the segment.
Octagon = square of diameter of inscribed circle × 0.828.
Hexagon = square of diameter of inscribed circle × 0.866.
Sphere = area of its great circle × 4; or square of diameter × 3.1416 (π).

Volumes

Prism = area of base × altitude.
Wedge = length of edge plus twice length of base × one-sixth of the product of the height of the wedge and the breadth of its base.
Cylinder = area of base × altitude.
Cone = area of base × one-third of altitude.
Sphere = cube of diameter × 0.5236.

Miscellaneous

Diameter of circle = circumference × 0.31831.
Circumference of circle = diameter × 3.1416 (π).

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